

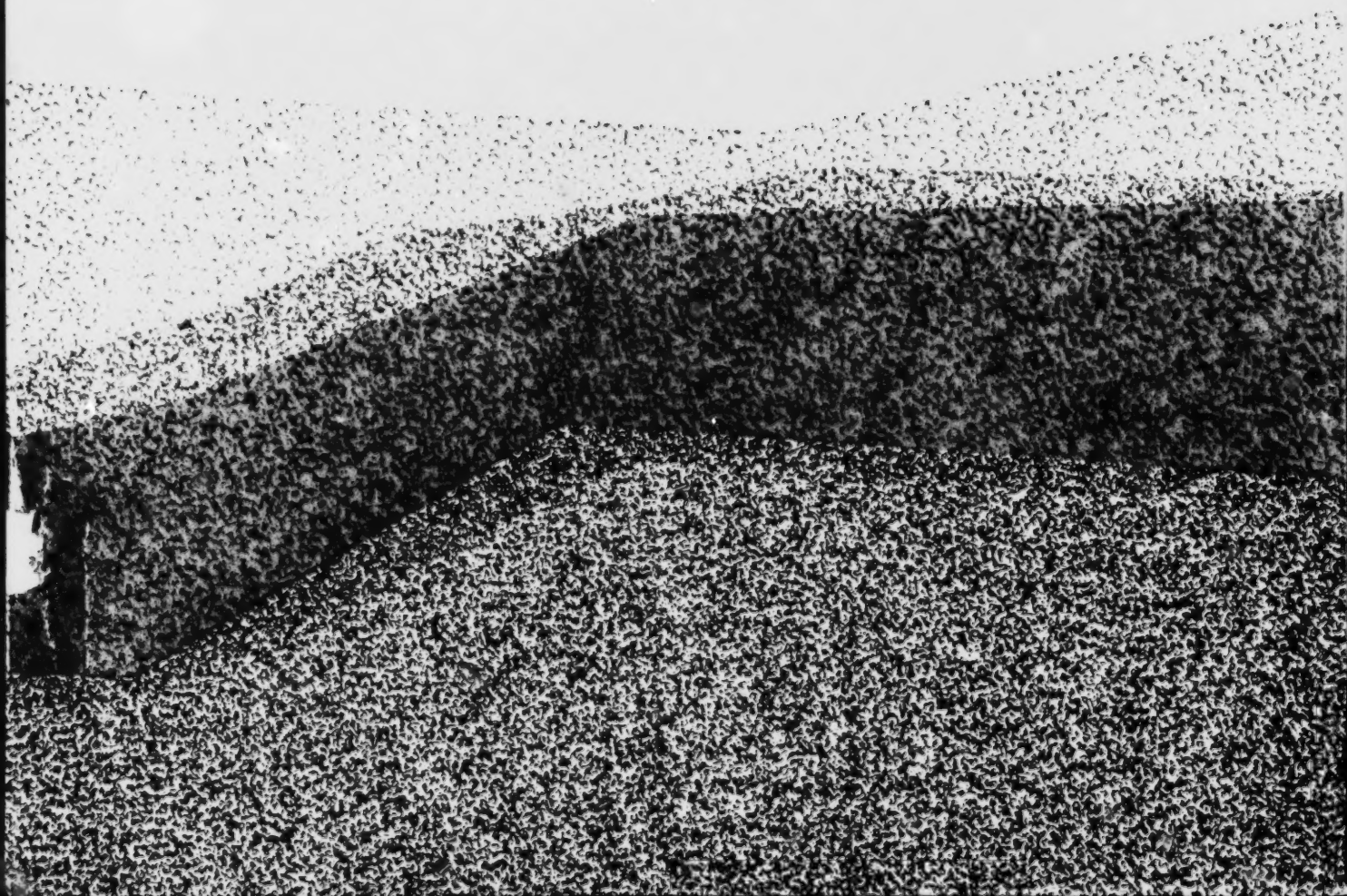
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Geological Aspects of Mining Productivity: Canada's Base Metal Resources

BRIAN W. MACKENZIE

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**Geological Aspects of Mining Productivity:
Canada's Base Metal Resources**

by
Brian W. Mackenzie

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PREFACE

The CRS technical paper series is designed to present detailed studies that provide background data and analysis of specific aspects of the Canadian mineral industry. It is hoped that this series will contribute to an understanding of the complicated concepts and interrelationships inherent in the industry, and to the development of rational public and corporate policies for the industry.

In this study, the author assesses the geological component of productivity in the base metal sector of the Canadian mineral industry, taking into account such factors as depletion effects, improvements in geological concepts and exploration technology, and metal price fluctuations. Both the methodology and the conclusions will be of interest to policy makers in government and industry, as well as to academic economists.

Views expressed are those of the author, and do not necessarily represent those of the Centre for Resource Studies or its sponsors.

Margot J. Wojciechowski
Centre for Resource Studies

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Finally, I would like to express my appreciation to the large number of Canadian mining companies which, over the past decade, have provided the base metal deposit data which form the basis for the case study.

SUMMARY

An evaluation procedure has been developed for examining effects of the geological characteristics of mineral resources on productivity change in the mining sector. Application of this methodology is intended to contribute to continuing dialogue on the role of mining in the Canadian economy.

A long-term view of the mining sector is adopted, considering time trends in productivity from the start of the mineral supply process, through exploration, development, and production phases. The study methodology provides absolute measures of the efficiency with which all "factors of production" - mineral resources, labour, and capital - are employed in mining.

Mining productivity is defined as the difference between the revenues realized from mineral production and all the exploration, development, and production costs required to realize that revenue, including an allowance for the cost of capital. The efficiency of the mining sector is measured by several expected value and risk criteria.

Factors of production other than mineral resources are evaluated on the basis of a standard set of present-day economic and technological conditions. In this way, all other "inputs" in the mining production function are held constant. This evaluation procedure permits the isolation and examination of relative changes in the geological aspects of mining productivity, namely the mineral exploration expenditures incurred, and the quality of mineral resources discovered. Observed time trends reflect the resultant of depletion effects, and advances in geological concepts and exploration technology.

Base metal resources have played an integral part in the growth and development of the Canadian mineral economy. The methodology developed is applied to assess geological aspects of productivity change in the base metal sector of the Canadian mineral industry. This case study examines some \$3.5 billion of exploration expenditures which have resulted in the discovery of 274 significant base metal deposits during a long historical timeframe, extending to 1977.

Examination of the combined impact of the geological characteristics reveals that base metal productivity trends appear to be flat at expected metal prices, decrease at lower-limit prices, and increase at upper-limit prices. However, the erratic nature of the findings makes these time trends difficult to discern. The fluctuating results are consequences of the highly variable nature of resource quality among deposits, and the high risk and therefore somewhat random character of mineral exploration.

With respect to the exploration expenditure component of productivity, a significant rise in discovery costs is apparent from the late 1940s to the early 1960s with no noticeable increase since then. This suggests that, for the past 20 years or so, the application of better geological models for area selection and the ranking of targets, together with new and refined exploration technologies, have been successful in countering the rising costs associated with greater depth, increasing remoteness, and sampling without replacement.

The quality of base metal resources discovered as the result of these expenditures has also been examined in detail. Mineral resource "quality" has a number of facets including deposit size, geological grade, geographical location, ore width, depth below surface, mineralogical complexity, and associated geotechnical properties. Appraisal of the changing quality of Canada's base metal resources is made by evaluating and comparing the development and production phase characteristics of economic deposits as a function of their discovery date. This analysis is carried out initially for all deposits taken together, and then for geologically consistent deposit-type groupings.

Although some of the study results may be subject to differing interpretations, the evidence presented does not in general support the hypothesis that the quality of Canada's base metal resources is declining. Certainly, ore grades within consistent deposit-type groupings have been maintained. Any modest deterioration in the productivity of base metal resources otherwise observed must be weighed against the bias, inherent in the data base, to undervalue more recent discoveries.

If this finding is in fact valid, why has the quality of base metal resources been maintained? Two main reasons are suggested. First, base metal exploration, despite much scientific study and practical experience, is a complex process which is still only poorly understood. The exploration process is not nearly as systematic as some would believe, and certainly does not proceed methodically from high quality to low quality discoveries. Scientifically-based exploration is no doubt better than purely random exploration, but perhaps not by much. Thus, it appears that depletion, in the guise of declining resource quality, manifests itself quite slowly and may lead to serious national consequences only over a timeframe even longer than that considered in this study. Canada's mineral resources are vast. While known mining districts are being more intensively explored, the geographical limits of the search process are still expanding into new unknown regions.

Second, the positive productivity effects of advances in geological concepts and exploration technology tend to be undervalued, possibly because they have not been fully documented and cannot be readily

measured. The results presented here for Canada's base metal resources suggest that the expanding scientific limits of the search process have been sufficient to offset the negative depletion forces. Consequently, resource quality does not appear to be declining.

The findings of this study call into question not only the widely held belief that the geological characteristics of Canada's mineral resources are declining, but also the negative overall trends which have been evaluated in mining productivity studies. If the efficiency of our mineral resources is not decreasing, it is hard to imagine, in light of mining and processing advances introduced during the study period but not accounted for here, that there has not been a positive rate of improvement in mining productivity overall.

The results do not deny the serious problems currently existing in the base metal mining sector. Mining in Canada, like the world-wide industry, is in the process of shrinking to a more profitable size as a result of market forces. The mine closures which have occurred since 1982 should indicate to policy makers, shareholders, and to Canadian society in general that each entity must be profitable in order to survive. These events do not, however, indicate that the nation's mineral resources are declining in quality or becoming exhausted.

Study findings suggest that, if base metal resources gave Canada a competitive advantage in international markets historically and played a key role in national economic development and prosperity, there is reason to believe that they can continue to do so well into the future. Canada's high-quality mineral resources are still essentially intact. The challenge is to shape their development to best suit the changes emerging in long-term international market conditions.



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1. INTRODUCTION

Study Setting

While *mineral resources*¹ and mining have been of undoubted importance to the economic development of Canada, their future role is uncertain. Has the Canadian mining sector reached a turning point? This question is as crucial to the formulation of economic development policy as it is complex and difficult to answer.

The issue, concerning the comparative advantage of mining relative to other sectors of the economy, has two main parts. The first relates to international mineral market conditions. To what extent does the prolonged market recession being experienced in the 1980s represent permanent structural change in mineral consumption, and to what extent does it reflect a temporary downward phase in an economic cycle of very long duration?²

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1. Terms initially italicized in the text are defined in a glossary for the non-technical reader.
 2. Company planning and government policy appear to be increasingly founded on the hypothesis that the weak mineral markets of the 1980s are *structurally* rather than *cyclically* depressed. Thus, permanent reductions in consumption growth rates are foreseen for most mineral commodities.

There is, however, another explanation of what is happening in the international marketplace based on the interplay of short-, medium-, and long-term economic cycles. In this regard, a 1976 paper by Grandison has proven to be rather prophetic, describing the approach of Placer Development in using leading economic indicators to predict these cycles. He forecast a serious recession in the early 1980s which "may result in an extended deflationary period - longer than any recession in the postwar period" to be followed in due course by "the second longest period of uninterrupted growth since the second world war". Grandison's advice was "to accumulate fat for the lean period ahead".

More recently, Yates advances the view that the 1980s will be a decade of readjustment, to be followed by a robust upcycle in metal prices. Likewise, Sutulov's diagnosis is that "we are living with the long-term effects of a depressive economic cycle, which is far from being over, and which implies that, the same as so many times in the past, once it is over, vigorous growth in metal consumption and demand will be reestablished". He predicts that the recovery, which may not arrive before 1990 or 1995, will be led by the industrialization of southeast Asia in general and China in particular.

Canadian economic development policy also cycles. The federal government's 1981 budget paper, Economic Development for Canada in the 1980s, highlighting natural resources, including minerals, as the leading opportunity for national economic growth, correlates with

The second part of the question concerns the productivity of the mining sector in Canada and its competitive standing relative to other major suppliers in international markets. Is the productivity and competitive position of Canadian mineral supply declining or improving with time?

While there are various components of mining productivity, including the changing mixture and efficiencies of labour and capital, perhaps the most fundamental, and certainly the most neglected, is the stock of mineral resources available for production. A factual understanding of time trends in the *geological aspects of productivity*³ is required to be able to appraise the future role of mining in Canadian economic development.

Objective and Scope of Study

The paper outlines a procedure for examining the economic effects of the changing nature of mineral resources on mining productivity. The methodology is applied to assess geological aspects of productivity change in Canada's *base metal* mining sector.⁴

50-year price peaks for several metals which occurred in 1979-81. In keeping with the continuing resources recession in the mid-1980s, the present mood is to shift emphasis away from natural resources into the production of goods and services requiring more knowledge, skills, and technology or, in other words, according to Maxwell, towards "smarter solutions". Lamontagne points out the serious forecasting and policy errors in Canada which have resulted from an inadequate understanding of economic cycles, and which have tended to exaggerate rather than reduce their undesirable effects.

See Grandison, C.A., "Economic Cycles as a Tool in Business Forecasting", CIM Bulletin, December 1976, pp. 58-62; Yates, E.M., "Metal Prices: Cyclical or Structural?", CRS Perspectives, August 1985; Sutulov, Alexander, "Canadian Role in Future Metal Markets", paper presented at CIM annual general meeting, Vancouver, April 1985, 14 pp.; Maxwell, Judith, "The Inevitable Move Away from Resources", Report on Business, May 1985, pp. 11-14; and Lamontagne, Maurice, Business Cycles in Canada: the Postwar Experience and Policy Directions, Canadian Institute for Economic Policy, 1984, 194 pp.

3. Geological aspects of mining productivity, as considered here, comprise all parameters directly associated with mineral resources which affect the economics of mineral supply, including the exploration expenditures required to find and delineate deposits; and the quality of the resources discovered, in terms of such facets as deposit size, grade and location.
4. The present study has evolved from preliminary consideration of one component of this topic, the quality of mineral resources discovered. See B.W. Mackenzie, "The Productivity of Canada's Mineral Resources: Is the Quality Declining?", pp. 61-95 in Mining Productivity, M. Wojciechowski (editor), proceedings no. 16, Centre for Resource Studies, Kingston, February 1985, 181 pp.

Organization of the Study

An outline of the study, its major findings, and the implication of results for government policy formulation are presented in the summary.

Chapter 2 examines conventional beliefs regarding the changing nature of mineral resources, offers an alternative view, defines productivity measurement, critiques the work on mining productivity which has been carried out in Canada, and introduces the notion of a geological component of productivity.

The evaluation procedure developed to assess the geological aspects of mining productivity and the productivity measures adopted are described in chapter 3. These geological characteristics are considered to have two aspects: *mineral exploration costs*, and the *quality of mineral resources* discovered.

Chapter 4 outlines the contribution of Canada's base metal mining sector and describes the assembly of data for the case study, including mineral exploration expenditures, possible economic discoveries for evaluation, general market estimates, and individual deposit estimates.

The overall effect of geological characteristics on productivity change in base metal mining is examined in chapter 5. Chapter 6 more specifically analyzes time trends in the exploration expenditure component of productivity. The changing quality of base metal resources is assessed in chapter 7, which examines time trends in the development and production phase characteristics of *economic deposits*.

Chapter 8 disaggregates base metal resources into several geologically consistent categories. This gives a clearer perspective of time trends, and provides an improved basis for examining the changing quality of base metal resources and consequent effects on mining productivity in chapter 9.

2. BACKGROUND

The purpose of this chapter is to place the study in context. Conventional beliefs regarding the changing nature of mineral resources are first examined and an alternative view proposed. The concept of productivity measurement is described, and the three main investigations of mining productivity in Canada are reviewed. Finally, the idea of a geological component of mining productivity is introduced.

Conventional Wisdom

There is a widely held view that the quality of mineral resources declines with time. Mineral resources are thought of as a fixed set of *mineral deposits* in the earth. Mining from this stock reduces or depletes the *ore reserves* remaining. This view of mining as a process of systematic depletion is formalized by "the pure theory of exhaustion" in economic theory.⁵

The pure theory of exhaustion assumes that the fixed set of mineral deposits is known. This leads to the supposition that minerals will become scarcer in the future as the finite stock of resources is exhausted by production. Also, since the known set of deposits is variable in quality, the theory presumes that mining activities rationally proceed in a sequential fashion from higher to lower quality ores.

The economic consequences of this notion of mineral supply have diverse and compelling policy implications. As the highest-quality, lowest-cost deposits are used first, costs will systematically rise as cumulative production increases. Thus, the Club of Rome advanced the argument in the early 1970s that the exhaustion of mineral resources provides a limit to worldwide economic growth and threatens the welfare of mankind.⁶

-
5. Vogley crystallizes the distinction between this physical approach to mineral depletion and the alternative economic approach introduced in the next section. See W.A. Vogley, "Resource Assessment and the Theory of Mineral Supply", Materials and Society, vol. 8, no. 4, 1984, pp. 597-600.

The basic concepts underlying the pure theory of exhaustion may be found in definitive treatments by Gray and Hotelling. See L.C. Gray, "Rent Under the Assumption of Exhaustibility", Quarterly Journal of Economics, May 1914, pp. 464-489; and Harold Hotelling, "The Economics of Exhaustible Resources", Journal of Political Economy, April 1931, pp. 137-175.

6. See D.H. Meadows, et al., The Limits to Growth, New York, Universe Books, 1972, 205 pp.

At a national level, as the cost of producing minerals increases, the comparative advantage of mining relative to other sectors of the economy declines. This perceived consequence underlies a belief, most recently expressed in the work of the Macdonald Commission, that the Canadian mining sector may have reached a turning point, and that its role in economic development should now be de-emphasized.⁷

Circumstantial evidence tends to support the conventional view that the quality of mineral resources is declining. For any single mineral deposit, there is a powerful economic incentive to sequence mining from higher to lower quality ores wherever possible, a common practice at operating mines. This economic rationale also tends to govern the order of development and exploitation among known mineral deposits. Intensively explored and developed mining districts are typified by increasing mining depths and, often, declining *ore grades*. Closures of mines and mining communities are inevitable consequences of the exhaustible nature of mineral deposits.⁸ More generally, based on a dismal economic performance since 1982, the Canadian mining sector looks like it is suffering from depletion. While this intuitively appealing view is widely held, it is broadly inconsistent with the actual behaviour of mineral resources over time.⁹

7. The Royal Commission on the Economic Union and Development Prospects for Canada, the "Macdonald Commission", was appointed in November 1982. The Commission appears to have taken a position against the idea of the resource industries as a leading sector for growth in the Canadian economy. In fact, Commissioners have suggested during the course of their hearings that mining might be a "sunset industry". The chairman, Donald Macdonald, told the press, in elaborating on the Commission's interim report Challenges and Choices, that Canadians must end their dependence on natural resource exports or face a drastic fall in their standard of living. The statements of some mining industry spokesmen tended to support this view by drawing a picture of a mining industry in extreme distress. The final Commission report, to be released in September, is to include a chapter specifically on the resources sector. See David Yudelman, Mining and the Macdonald Commission: the State of the Industry in the Mid-1980s, working paper no. 34, Centre for Resource Studies, Kingston, 1985.
8. "Picking up the pieces" has always been a prominent aspect of Canadian mineral policy, from the Emergency Gold Mining Assistance Act and Cape Breton coal subventions, to more recent concerns about Schefferville, Cyprus Anvil, and Lynn Lake.
9. However, findings by Wedge in the early 1970s do support the conventional view, using a statistical proxy for the ore grade dimension of mineral resource quality. He estimated that the quality of ores mined in Canada declined by an average of 3.7 percent per year during the period 1957-67. See T.A. Wedge, "The Effect of Changing Ore Grade on the Rates of Change in the Productivity of Canadian Mining Industries", CIM Bulletin, November 1973, pp. 64-66.

An Alternative View

Another view of mineral resources, supported by empirical evidence, offers a useful explanation of the changing nature of mineral resources. According to this view, outlined by Vogley, resources are thought of as the working inventory of a process of mineral supply. They are efficiently provided as needed by investing in mineral exploration, technology, and mine development.

Consistent with this idea, mineral deposits are not only fixed in size and variable in quality, they are also initially unknown. Thus, exploration, a high-risk activity, with no counterpart in other economic sectors, is necessary prior to the development of productive capacity. Exploration introduces a random element into the supply process, since it is not practically possible to find the better deposits first and then proceed systematically to lower quality discoveries. Also, while known mining districts are being more intensively explored, the frontiers of the search process are being extended into new unknown regions. At the same time, advances in geological concepts and exploration technology act to relax the scientific limits of exploration.

Given these circumstances, it is arguable whether the quality of mineral resources revealed by successful exploration and thus available for mining declines with time. Also, there is the additional consideration of time trends in exploration costs required to find these deposits.

Our particular interest is the role of mining in the long-term economic development of Canada, a country endowed with vast, complex, and still largely unknown mineral resources. The issue at hand is whether time trends in exploration costs and in the quality of mineral resources discovered (i.e., the geological aspects of mining) are having a negative, neutral, or positive influence on the productivity of the Canadian mining sector.

While historical evidence is far from complete, several Canadian resource-based studies do not support the conventional hypothesis that the geological aspects of mining productivity are deteriorating. Cranstone¹⁰ shows that the value of minerals discovered in Canada per dollar of exploration expenditure has remained relatively constant since the second

10. D.A. Cranstone, "Canadian Mineral Discovery Experience Since World War II", paper presented at International Institute for Applied Systems Analysis, Laxenburg, Austria, December 1983, 64 pp.

world war. A study by Martin and Jen,¹¹ analyzing the grade of ore extracted from mines in Canada over the last 50 years, concludes that average ore grades have improved for some conditions and have shown no signs of decline for others. In the few cases where modest declines are evident, this is found to be attributable to advances in technology enabling the mining of lower grade deposits, rather than to the effects of exhaustion. Mackenzie¹² analyzes the present-day economic viability of 275 base metal deposits discovered in Canada to 1977, classified by discovery dates. The time trend in the average net present value of the deposits which are found to be economic does not in general support the view that the quality of mineral resources is declining. The highly visible examples of Kidd Creek and Hemlo also contradict the conventional view. They are among the highest quality base metal and gold deposits found in Canada to date, are neither remote nor deep, and were discovered as recently as 1963 and 1981 respectively.

The conflicting views and evidence reviewed here can only lead to the conclusion that in Canada we do not at present know what effect the geological characteristics of mineral resources are having on productivity change in the mining sector. In further examining empirical evidence, the present study adopts the alternative view, considering mineral resources in the context of a long-term supply process, in an attempt to shed more light on these time trends.

Productivity Measurement¹³

The term *productivity* encompasses a variety of measures which may be used to evaluate the efficiency of production or, in other words, the rate at which output flows from the use of given amounts of the *factors of production*. These factor inputs may be broadly grouped into land, labour, and capital categories. Renewable and nonrenewable natural resources, including mineral deposits, comprise the land factor of production. Inter-industry inputs, including supplies, capital equipment, and services produced in other sectors of the economy may be considered as a separate factor of production.

11. H.L. Martin and L.S. Jen, "Are Ore Grades Declining? The Canadian Experience, 1939-89", paper presented at International Institute for Applied Systems Analysis, Laxenburg, Austria, December 1983, 51 pp.
12. B.W. Mackenzie, Economic Mineral Exploration Targets, Working Paper 28, Centre for Resource Studies, Kingston, January 1984, 63 pp.
13. For more detailed information on the concept of productivity, the interested reader is referred to: S. Fabricant, "Productivity", in International Encyclopedia of the Social Sciences, vol. 12, The Macmillan Company and the Free Press, New York, 1968, pp. 523-536.

In order to measure productivity, empirical relationships are developed to link output with one or more of the required factor inputs. If assessments reveal that factors are being used inefficiently, there will be scope for productivity improvements, since by definition more output can be produced by more efficient use of the given amounts of inputs.

The type of productivity measure used depends on the policy or planning issue which needs to be addressed. If productivity is measured by expressing output as a ratio to one selected factor input, the input selected will give its name to the productivity measure. For example, "labour productivity", expressed as production per person employed or tonnes per man-shift, is the ratio of output to labour input. Such single-factor indicators may provide simple and useful guidelines for mine planning and control. However, care must be taken in making comparisons across mines, companies, sectors, or countries on the basis of only one productivity indicator, since differing geological, technological, and economic conditions may mean that different productivities of specific inputs are quite consistent with efficiency.

Serious attempts to assess the changing productivity of an industry, such as mining, for government policy purposes, require a more complete measure of the efficiency with which all the factor inputs combined are employed in production. This type of economic indicator, the focus of attention in the present study, is usually referred to as *total factor productivity*. Specifically, we are concerned with the changing influence of the geological aspects of mineral resources, the land input in this case, on the total factor productivity of mining.

The purpose of productivity studies is to monitor and explain time trends. Based on historical evidence, what has been the direction and rate of productivity change, and why? The measurement of trends in total factor productivity generally involves the following steps:

- specification of the economic activity to be examined;
- definition of a time period over which productivity trends are to be assessed;
- assembly of time series of data for output and related inputs, including the specification of units;
- formulation of an appropriate production function model to link output and inputs;
- determination of weights to standardize and combine units for the various factor inputs;
- statistical analysis to estimate changes in the relationship between inputs and output over time, normally expressed as an index of productivity;
- interpretation and explanation of results to provide policy guidelines.

Productivity studies normally set out to analyze actual historical experience. In reality, all factor inputs are in fact varying. Ideally, the measurement of total factor productivity evaluates the extent to which changes in output are not matched by the combined changes in all factor inputs. In practice, however, it is not usually possible to assemble historical time series information for all of the inputs. This limits the realism of the analysis and the explanatory power of the productivity measures.

Most studies of total factor productivity in fact restrict attention to the relationship between output and the labour and capital inputs. Even in these cases, statistical measurement and weighting difficulties are encountered. More fundamentally, there is a conceptual problem: while labour and capital may be the most important factors of production, they are certainly not the only ones, especially for resource-based industries such as mining. Thus, changes in the relation between production and the labour-capital inputs may represent substitution by or for other factors of production not included in the evaluation. Results cannot therefore be directly attributed to changes in total factor productivity and, consequently, practical difficulties are encountered in interpreting the findings of such analyses.

Mining Productivity in Canada

Three principal studies have been made of mining productivity in Canada: Dawson,¹⁴ Anton,¹⁵ and Stollery.¹⁶

John Dawson, then with the Economic Council of Canada, was the first to go beyond measures of labour productivity to find out how the combined productivity of labour and capital was changing in the mining sector. Dawson's measure of combined productivity, termed "factor productivity", represents changes in mining output other than those accounted for by changes in labour and capital inputs. Such a measure provides a better indicator than labour productivity of the direction and rate at which the efficiency of mining is changing, because increasing labour productivity may be obtained by substituting capital for labour without increasing overall efficiency.

14. Dawson, J., Productivity Change in Canadian Mining Industries, staff study no. 30, Economic Council of Canada, 1971, 61 pp.
15. Anton, F.R., "Productivity in the Mineral Industry", preliminary report for the Department of Energy, Mines and Resources, Ottawa, 1973, 259 pp.
16. Stollery, K.R., Productivity Trends and their Causes in the Canadian Mining Industry, 1957-79, discussion paper no. 248, Economic Council of Canada, December 1983, 86 pp.

Thus, Dawson analyzes growth in the Canadian mining sector during the 1947-67 period in relation to the labour and capital required to achieve that growth. The economic activity considered includes gold, iron ore, other metal mining, coal, petroleum and natural gas, asbestos, and other nonmetal mining. A data base is assembled to measure rates of increase in mining output relative to rates of change in labour and capital inputs.

Overall mining sector results show an average annual increase in factor productivity of 4.5 percent for the first postwar decade falling off to 0.3 percent per year in the second decade. A marked shift in relative importance, away from gold and coal mining and towards petroleum and natural gas production, is associated with the high rate of productivity improvement during the 1947-57 period. A more specific assessment of the component mining industries for the period 1957-67 highlights the heterogeneous nature of the mining sector. The average annual rate of productivity change, 0.3 percent overall, is found to vary from +4.3 percent for iron ore mining to -0.8 percent for gold mining.

Dawson is careful to acknowledge a number of limitations associated with the data base and methodology employed, including the following:

- the relationship between the cost of inter-industry inputs to mining and output is assumed to remain constant;
- exploration expenditures, other than for petroleum and natural gas, are not included;
- the mineral resource input is not explicitly considered, the assumption being made that the use of mineral resources increases at the same rate as the capital input;
- a number of problems arise in measurement of the capital input. Estimates of gross capital stock, a static indicator, are mainly used. No allowance is made for the changing rates of capacity utilization associated with mining output. Also, the time lag between investment and output is not considered.

Thus, the productivity indicators calculated by Dawson represent the changes in mining output which have occurred other than those accounted for by the changes in labour and capital inputs. Apart from increased efficiency in the use of all factor inputs, these results could be attributable to changes in the relative cost of inter-industry inputs, the effects of the excluded exploration expenditures, changes in the quality of mineral resources utilized, and the imprecise relationship between the estimated capital stock and mining production. What, then, do these re-

sults mean in terms of changes in the efficiency of mining? While the changing quality of the mineral resource input is not evaluated, Dawson suggests that "greater amounts of capital employed in exploring for, and developing, lower-quality, deeper, or more remote deposits is an element in the observed decline in the rate of increase in factor productivity in the mining sector".¹⁷

Anton's unpublished study parallels the work of Dawson. The time frame is extended to 1972. Overall results indicate that since 1960 mining productivity has ceased to increase and has shown a slight tendency to decline. Possible explanations for this observed trend are considered. A more detailed examination is made of productivity change for the component mining industries.

Once again, the estimated productivity indicators tell us little directly about the changing efficiency of the mining sector. The remainder of Anton's study concerns labour market conditions, productivity measurement for corporate planning, the opportunity to increase productivity through labour-management agreements, and other labour-related productivity issues.

Anton, like Dawson, does not explicitly evaluate the changing quality of mineral resources. However, statements such as "the greater inputs of capital and labour required to explore and produce these distant, lower-quality or deeper minerals have hampered the rate of increase in factor productivity"¹⁸ suggest that he too believes the quality is declining.

17. Dawson, Productivity Change, p. 19. Wedge adjusts Dawson's estimated rates of productivity change for a statistical measure of the average annual rate of change in the grade of ore mined. This correction gives factor productivities more dependent on changing efficiency in the use of labour and capital and less dependent on the effects of unquantified changes in factor inputs. The statistical measure employed shows that the grade of ore mined has declined over time. Wedge argues that this trend provides a conservative estimate of the amount of productivity improvement which must be obtained in the use of labour and capital inputs to overcome the decline in the quality of mineral resources mined. Wedge's revised productivity figures show dramatically different trends in the efficiency of labour and capital employed in mining than do those assessed by Dawson. For example, the increase in factor productivity, estimated by Dawson at 0.3 percent per year for the mining sector during the 1957-67 period, is adjusted to 4.2 percent per year. T.A. Wedge, "The Effect of Changing Ore Grade on the Rates of Change in the Productivity of Canadian Mining Industries", CIM Bulletin, November 1973, pp. 64-66.

18. Anton, "Productivity in the Mineral Industry", p. 71.

Stollery formulates and applies a more ambitious and theoretically appealing productivity model, intending to overcome some of the limitations of the two earlier studies. Thus, ore grades, the cost of energy inputs, and a variable which reflects both the scale of operations and capacity utilization, are incorporated in the productivity function developed. Productivity indices are assessed for the mining sector overall, and its component industries, during the period 1957-79. Time trend results are given for the 1957-65, 1966-70 and 1971-79 intervals. Evidence presented indicates a declining trend in total factor productivity, interpreted to be one of the worst and longest lasting among the economic sectors in Canada, beginning in the mid-1960s. A perceived decline in the grades of ore mined is shown to make a significant contribution to the decline in mining sector efficiency. On the other hand, the effects of higher energy costs and wage increases appear to be weak.

Stollery's treatment of the mineral resource input has two shortcomings. First, ore grade represents only one of several facets of the quality of mineral resources. Secondly, the definition and measurement of the grade variable employed can at best be described as uninformed. Grade estimates are based on concentrate rather than ore content. For *poly-metallic deposits* each metal is given equal weight. Where there are major differences in the weights and values of component metals, as in the case of precious metal byproducts, ore grade estimates are based on the dominant metals only.¹⁹ Consequently, Stollery's mining productivity indices and their policy implications can only be viewed as suspect.

Stollery appears to hold contradictory views concerning the quality of mineral resources. His contention that the process of mineral exploration and discovery is essentially random implies that there should be no systematic trend in the quality of deposits found. However, he also states several times that, since the best ore is exploited first, ore grade or quality declines with time. Indeed, this assumption is embodied in the productivity model developed.²⁰ The study results appear to substantiate this supposition. For example, a key finding is that a 60-percent reduction in the average grade of ore mined in the copper industry from 1957-65 to 1971-79 has had a significant impact on reducing productivity. Leaving aside the important issue of how the associated lead, zinc, molybdenum, silver, and gold grades have been treated, this is a questionable inference. High grades in small, remote, deep, narrow, complex orebodies may not be as productive as low grades in large, accessible, sim-

19. Martin provides a critique of Stollery's determination of ore grades. H.L. Martin, "Comments on K. Stollery's Paper", pp. 56-60 in Mining Productivity, M. Wojciechowski (editor), proceedings no. 16, Centre for Resource Studies, Kingston, February 1985, 181 pp.

20. Stollery, Productivity Trends, pp. 7-8.

ple, surficial deposits. Thus, observed grade trends may have resulted from economic choice rather than geological necessity. Although Stollery uses the terms synonymously, there is an important distinction between the grade and the quality of mineral resources.

Geological Aspects of Mining Productivity

An inherent difficulty in measuring mining productivity, highlighted by the three main Canadian studies and further discussed by Wedge and Green, is the uncertain, variable and changing character of the mineral resource input. These geological aspects of mining productivity are not adequately understood. Real trends in mining productivity will remain a matter of contention, misinterpretation, and unsubstantiated belief until the necessary knowledge is obtained.²¹ The mining sector has been too important to the prosperity of Canada to consider changes in economic development policy without first understanding these trends.

21. A recent study by Green of gold mining productivity in Ontario during the 1966-77 period provides an excellent example of the understanding of productivity trends which is possible by careful compilation of statistical data, specifically focused, and comprehensively analyzed and interpreted. See A.G. Green, Productivity and Price: the Case of Gold Mining in Ontario, Working Paper No. 32, Centre for Resource Studies, Kingston, 1983, 46 pp.

3. EVALUATING THE GEOLOGICAL ASPECTS OF MINING PRODUCTIVITY: THE METHODOLOGY

The purpose of this chapter is to describe the methodology developed to assess the geological aspects of mining productivity.

Terms of Reference

We wish to examine the effect of the geological characteristics of the mineral resource input on productivity change in the mining sector. The evaluation procedure adopted provides absolute measures of total factor productivity. The intended application requires the methodology to differ in several respects from conventional econometric methods, including those used in the mining productivity studies reviewed in chapter 2. Conventionally, mining productivity studies attempt to analyze the combined effect of all factor inputs and to explain the consequent results. Even though it may not be possible to measure all the variables, they are in fact all changing with time.

Productivity change can also be assessed with one or more of the factor inputs held constant, as in an experiment carried out under controlled conditions. While such a situation does not fully represent actual experience, results may shed light on the influence of a particular input of interest. This approach is adopted in the present study. To isolate and examine the effect of the mineral resource input on mining productivity, the other factors of production are valued with reference to a particular point in time, and are, therefore, assumed to remain constant.

More specifically, the methodology employed differs in the following respects from previous studies of mining productivity in Canada:

- deposit-specific data rather than aggregate government statistics are used;
- information and estimates are defined in *cash flow* terms instead of *accounting* terms;
- a *discounted cash flow analysis* procedure is utilized rather than statistical analysis in the form of an econometric model;
- no attempt is made to assess overall historical productivity trends. Instead, attention is confined to the effect of the mineral resource input on mining productivity;

- a long-term view of the mining sector is adopted, considering time trends in mineral exploration and the quality of mineral resources revealed through discovery. Thus, mineral resources are classified on the basis of discovery dates for individual deposits, rather than in terms of when the mining of ore actually takes place;
- all inputs and outputs are measured in constant dollar terms;
- factors of production other than the mineral resource input are evaluated on the basis of a standard set of present-day economic and technological conditions. In this way, other labour, capital, and interindustry inputs to the mining production function are held constant. This procedure means that time trends in the absolute measures of total factor productivity assessed are solely attributable to changes in the geological characteristics associated with the mineral resource factor of production.

This methodology enables us to isolate changes in mining productivity arising from depletion and from advances in geological concepts and exploration technology, based on observed variations in exploration costs and the quality of mineral resources discovered. The concept of "the mineral supply process" which follows provides a framework for assessing the economic productivity of mining required for this purpose.

The Mineral Supply Process

The process of attaining economic production of minerals consists of a multi-stage series of activities by which minerals are converted from unknown geological resources to marketable commodities, as portrayed in figure 1.

The physical occurrence of mineral deposits in nature and the demand for mineral commodities in the economy provide the basic stimuli for mineral supply. Favourable perceptions of exploration geologists and market researchers regarding these geological and market factors combine to guide the selection of environments for exploration.

The mineral exploration phase is a sequential information-gathering process. In the primary exploration stage, potentially favourable areas of land are initially selected within an environment of interest. These areas are then subjected to a series of geological, geophysical, and geochemical tests. The successful result of primary exploration is the *discovery of mineral occurrences*. At this stage the ultimate size and value of each mineral occurrence is unknown.

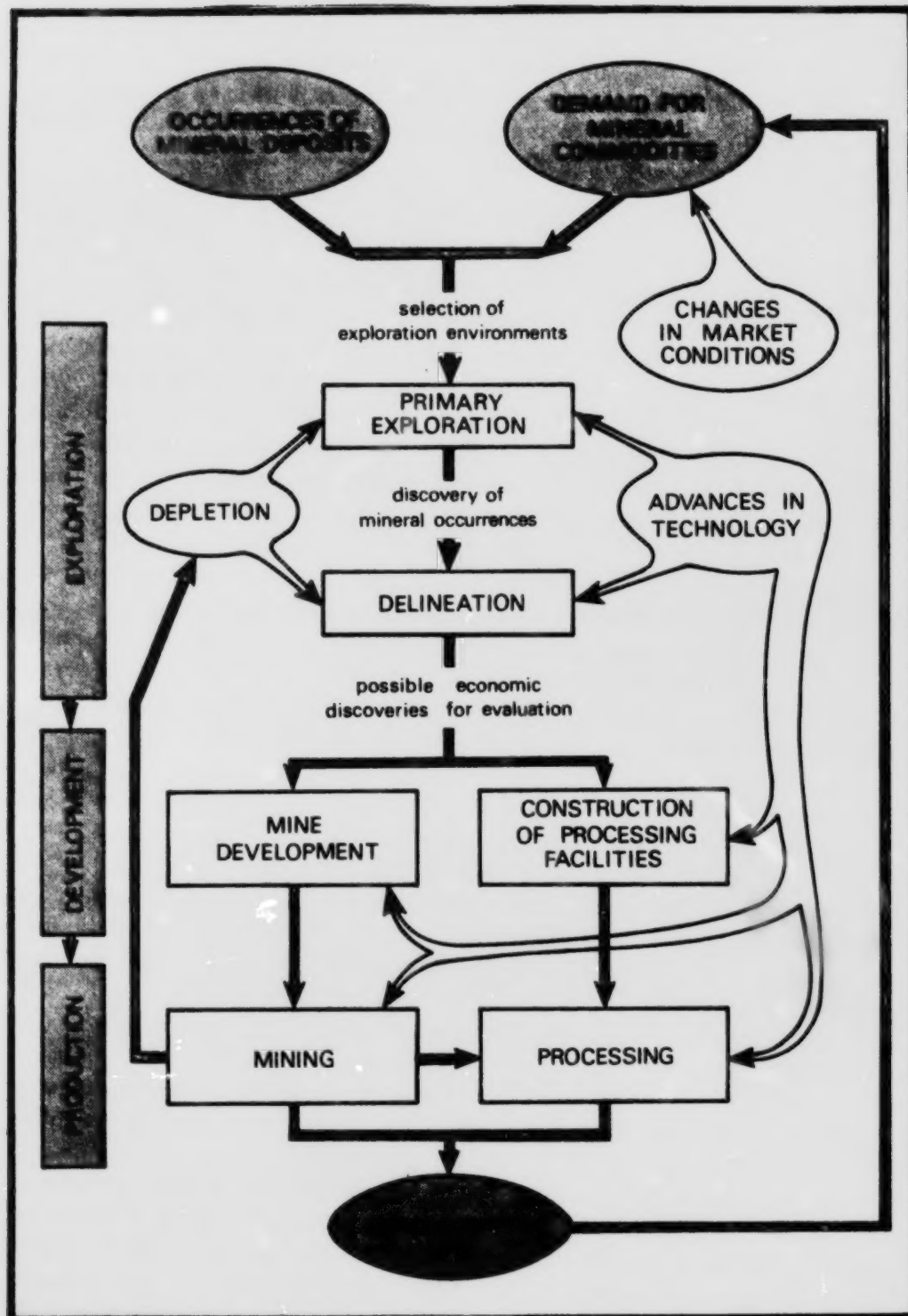


Figure 1. The Mineral Supply Process

The mineral occurrences discovered provide justification for the second, or delineation, stage of exploration when information is provided for estimating the size, grade, and physical characteristics of the discovery relevant to mineral or metal recovery. The successful result of delineation is the definition of possible economic discoveries for evaluation.

When sufficient delineation has been completed, a decision is made which determines whether a mineral deposit should be developed to production. If the characteristics of the delineated deposit provide justification for mine development, what is perceived to be an economic mineral deposit is the end result of mineral exploration.

The development phase establishes productive mining and mineral processing capacity. Processing is required to upgrade the mine product (ore) to a mineral concentrate for transportation and sale. Thus, the construction of processing facilities is carried out in phase with mine development. The installation of a mill at the minesite may be required or a common processing facility may be used to treat ores from a number of mines in a region.

When a mine has been developed and related processing facilities constructed, the production phase commences. The mining phase may include the stripping of waste for open pits, the preparation of stopes for underground mining, the development of ore reserves, drilling, blasting, materials handling to the processing facilities, the filling of mined-out stopes, and associated technical and planning services. For base metal operations, the processing stage usually includes crushing, grinding, flotation, drying, tailings disposal, and the loading of concentrate products for shipment.

The end result of the mineral supply process as considered in this study is the production of metal concentrate at the minesite to satisfy market demand. Market demand conditions include product transportation, smelting and refining activities, as well as the sale of metal in the ultimate market.

The mineral supply process is dynamic. First, the market demand for mineral commodities changes with time due to a number of factors, including: varying requirements of existing end uses; changes in the properties and relative costs of substitute materials; the development of new product markets; and modifications in transportation, smelting, and refining conditions. Secondly, depletion, the physical exhaustion of mineral deposits, is inherent in their exploitation. Thus, continual exploration is required just to sustain the existing level of mineral production. Furthermore, exploration, guided by geological concepts and skills, is to some extent a systematic process in the long term which, generalizing through the random and unexpected outcomes associated with exploration's

high risk, tends to detect first those deposits that are largest, highest grade, closest to surface or closest to market. Consequently, the best, easiest-to-find, deposits will on average be discovered, developed and exhausted first. Lower quality, smaller, or harder-to-find deposits remain for the future. Thus, depletion causes the cost of mineral supply to rise over time.²² Fortunately, there is a third offsetting dynamic force which is also at work: advances in technology. Such advances may include more efficient and extensive exploration techniques, and improved mining and mineral processing methods. Advances in technology act to reduce the cost of mineral supply. The resultant of these market, depletion, and technological forces determines whether the economics of mineral supply are in fact deteriorating or improving with time.

Mining productivity may be evaluated in terms of the economics of this mineral supply process. This provides a basis for examining the effects of the geological characteristics embodied in the process on productivity change.

Procedure for Evaluating the Productivity of Mining²³

Mining productivity is evaluated here by the costs, risks, and returns of the three-phase mineral supply process. We wish to determine time trends in absolute productivity measures attributable to the changing character of the mineral resource input.

The focal point of the mineral supply process is economic mineral deposits. Consequently, mining productivity indicators are derived from estimates of the exploration expenditures, development costs, and operating revenues and costs associated with an economic deposit.

The productivity of mining is assessed on a potential value basis.²⁴ Thus, all the costs and revenues directly associated with the mineral supply process are taken into account in the evaluation, including an allowance for the *cost of capital*. Since the cost of capital is deduc-

22. This aspect of the mineral supply process is the basis for the conventional view of mining trends discussed in chapter 2.

23. The approach discussed here extends a methodology which has been developed at the Centre for Resource Studies over the past decade. For further details of the evaluation procedure, see B.W. Mackenzie and M.L. Bilodeau, Economics of Mineral Exploration in Australia: Guidelines for Corporate Planning and Government Policy, Australian Mineral Foundation, Adelaide, 1984, 171 pp.

24. We do not consider the application of mining taxation to the overall potential return. Thus, the effect on productivity of how this potential return may be shared between industry and government is not evaluated. However, the potential value level of assessment provides a more basic insight into the productivity of mineral resources.

ted, this potential value represents the increase in real wealth which results from investing in mining rather than in some other economic activity.²⁵ Thus, potential value assesses the productive capability of the mining sector. In other words, potential value is our way of evaluating the relationship between output and inputs in the mining production function.

The data base for assessing the potential value associated with an economic deposit comprises the documentation of actual mining experience over a relevant historical time period, 1946-77 in the base metal case study introduced in chapter 4. We wish to evaluate this empirical information in a particular way. The geological aspects of the mineral resources input vary with time, individual deposits being classified on the basis of their discovery dates. All of the other labour, capital, and inter-industry factors of production are held constant by appraising the historical experience in the context of a standardized set of current economic and technological outlook conditions. This procedure allows us to examine the effect of changing geological characteristics within the mineral supply process on the productivity of mining.

In essence, the methodology (outlined in figure 2) follows these steps.

1. Total exploration expenditures are estimated for the historical time period of interest.
2. Significant deposits discovered as the result of these expenditures are classified by discovery date and listed for evaluation.
3. The development and production phase characteristics for each of these possible economic discoveries are evaluated on the basis of current outlook conditions.
4. Those discoveries which on evaluation satisfy minimum acceptable size and profitability conditions are considered to be economic deposits.
5. The development and production phase characteristics of all economic deposits are averaged.
6. Total exploration expenditures, which can not in general be directly associated with the economic discoveries, are prorated across all economic deposits evaluated.

25. The cost of capital is a real cost which affects the new wealth created by the mining sector.

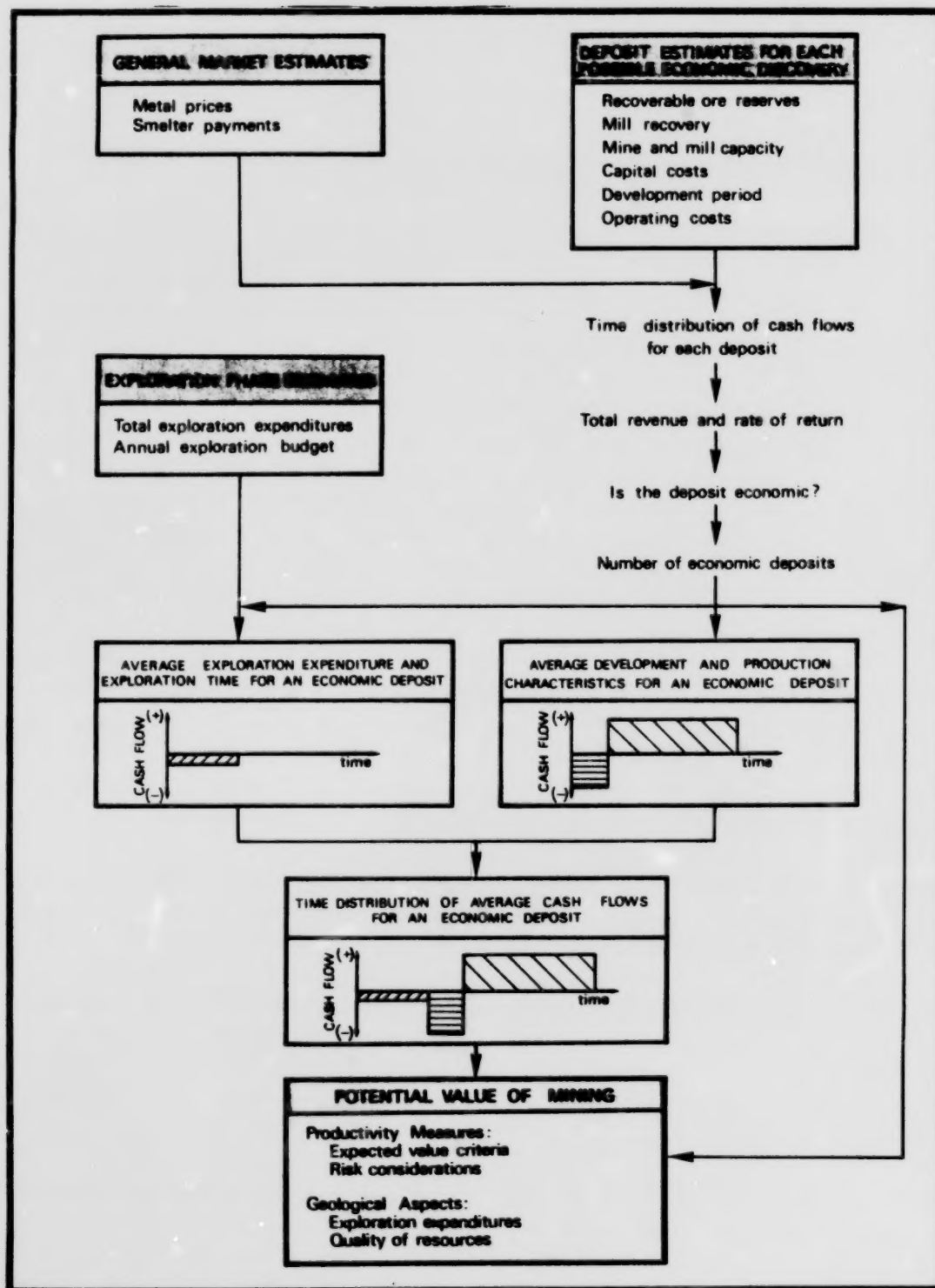


Figure 2. Procedure for Evaluating the Productivity of Mining

7. The exploration phase estimate is integrated with the average development and production phase characteristics to portray the time distribution of average costs and revenues for an economic deposit from the start of exploration to the end of production.
8. Several absolute expected value and risk measures of mining productivity are derived from these results. Time trends in these indicators reflect the changing geological character of the mineral resource input.

More specifically, the development and production phase characteristics for each of the possible economic discoveries (step 2) are evaluated (step 3) as shown in figure 2 by combining general estimates of metal prices and *smelter payment terms* with individual deposit estimates of *recoverable ore reserves*; *mill recovery factors*; *stripping ratio* for open pits; *mine and mill capacities*; *capital costs*, including the *working capital requirement*; *preproduction development period*; and *operating costs*. These estimates, based on the actual historical record, attempt to portray how each of the deposits would look today if awaiting development. A number of measures of economic worth are derived from the resulting cash flow distributions, including the total sales revenue generated and rate of return. Those discoveries which satisfy minimum acceptable total revenue (size) and rate of return (profitability) conditions are deemed to be economic (step 4). The cash flow estimates for all economic deposits are then averaged (step 5), resulting in a time distribution of average cash flows for the development and production phases of the mineral supply process.

With respect to the exploration phase appraisal (step 6), the total exploration expenditure estimate (step 1) is divided by the number of economic deposits assessed (step 4), to determine the average exploration expenditure required to find and delineate an economic deposit. This average exploration expenditure is then divided by an assumed most-efficient annual exploration budget rate to evaluate the average exploration time which would be needed to make an economic discovery. These exploration phase estimates are then integrated with the development and production phase appraisals.

As portrayed in figure 2, the end result of this evaluation process is an assessment of the time distribution of average cash flows for an economic deposit over the entire mineral supply process (step 7). The productivity indicators which may be derived from these estimates to isolate and explain the geological aspects of mining productivity change (step 8) are described in the next two sections.

Absolute Measures of Mining Productivity

Following the evaluation procedure developed, the productivity of mining may be expressed in terms of a number of economic criteria which may be conveniently subdivided into long-term and short-term considerations. The long-term efficiency of mining is evaluated using measures of expected value. The short-term problems associated with realizing expected values are assessed by risk criteria.

These absolute productivity measures are calculated using data for only those discoveries which satisfy the minimum acceptable economic deposit conditions specified. The number of economic deposits evaluated represents the statistical sample size on which the average return characteristics are based.

Expected Value Criteria

Expected value measures the average value that mining yields in the long term, when the successes and failures associated with a very large (theoretically infinite) number of discoveries are considered. The expected value of exploration is derived from the time distribution of average cash flows for the discovery of an economic mineral deposit, as portrayed in figure 2. Because of time value considerations, the average cash flow characteristics must be brought to a common point in time or spread evenly over a common period of time to make a valid assessment. The following two measures of expected value are applied in this study.

i Expected Value per Economic Discovery

An exploration expenditure E is required on average for the discovery and delineation of an economic deposit, yielding an average return R . Thus:

$$EV = R - E$$

where EV = expected value per economic discovery;

R = average net return from development and production associated with the discovery of an economic mineral deposit;

E = average exploration cost required to find and delineate an economic deposit.

To make a valid comparison, R and E are expressed as discounted values at the start of the exploration phase, using a cost of capital estimate for investment funds as the discount rate.

The higher the EV assessment, the more productive mining is perceived to be in the long term. Usually an expected value per economic discovery greater than zero is regarded as a necessary condition for investment. A negative EV signifies that exploration is an unacceptable investment in the long term, with more money going into the ground in discounted terms than coming out.

The expected value per economic discovery is analogous to the net present value criterion generally used in evaluation practice. As such, this measure reflects the intrinsic economic value of mining. Thus, EV comprises both size and profitability components.

ii Expected Rate of Return

The expected discounted cash flow rate of return on investment may also be evaluated based on the time distribution of average cash flows for an economic deposit as depicted in figure 2. By definition, rate of return is the discount rate which equates the present value of the positive cash flows with the present value of the investment. In economic terms, rate of return is the average percentage annual return that mining is expected to yield over the life of the mineral supply cycle. Using this method, the minimum acceptable condition for long-term exploration investment is an expected rate of return equal to the cost of capital.

Expected values are assessed in this study on the basis of overall mining activity and reflect the average performance of all organizations which have undertaken investment. Obviously, there are benefits to be gained from the application of superior skills and selectivity. In geological environments characterized by unacceptable overall expected values, the selection of opportunities of above-average merit is a necessary condition for long-term success.

Risk Considerations

There are three types of risk associated with the realization of expected values:

- i the uncertainty of the return associated with economic discoveries, arising from variability in tonnage, grade, and other geological characteristics among economic deposits;

- ii the risk associated with the discovery of economic mineral deposits;
- iii the sensitivity of mining revenues to metal price uncertainties.

These risks, individually and collectively, present challenges to the long-term profit, survival, and growth of mining organizations. While actual changes over time in the first two risks no doubt affect the productivity of mining, they are considered to be beyond the scope of the present study.

The third risk is associated with mineral commodity markets. There is typically a high level of uncertainty associated with the forecasting of short-term fluctuations and long-term trends in mineral market prices, including exchange rate risks. The time trends in mining productivity examined in the present study are estimated for a wide range of long-term metal price projections.

Geological Aspects of Mining Productivity Change

The effects of changes in the mineral resources input on the efficiency of mining are assessed by the absolute measures of total factor productivity described above. In seeking explanations for these time trends in the geological aspects of mining productivity, the two main components - exploration expenditures and the quality of mineral resources discovered - are subjected to the following more detailed examinations.

Mineral Exploration Expenditures

Trends in exploration expenditures reflect the interplay of four dynamic elements:

- changing rates of economic discovery;
- depletion effects in terms of increasing exploration difficulty;
- real changes in the costs of labour and inter-industry inputs to exploration;
- advances in geological concepts and exploration technology in terms of lower discovery costs.

This exploration expenditure component of mining productivity is assessed by the following indicators:

- average undiscounted exploration expenditure per economic discovery;

- average exploration period required to find and delineate an economic deposit;
- average exploration expenditure per economic discovery expressed as a discounted value at the start of exploration, E.

Quality of Mineral Resources Discovered

Changes in the quality of mineral resources are the resultant of two dynamic elements:

- depletion effects in terms of lower-quality economic discoveries;
- advances in geological concepts and exploration technology embodied in the geological characteristics of discoveries.

The quality of mineral resources has a number of facets, including:

- deposit size;
- geological grade;
- geographical location;
- ore width;
- depth below surface;
- mineralogical complexity;
- geotechnical properties.

Deposit quality affects the selection of mining and processing methods, recoverable ore reserves, mineral processing recoveries, stripping ratio, scale of operation, sales revenues, and capital and operating costs. Thus, the quality of mineral resources is a critical aspect of mining productivity.

The quality of mineral resources discovered is examined using the following measures of average characteristics for an economic deposit:

- return from development and production for an economic deposit expressed as a discounted value at the start of development;
- rate of return for an economic deposit based on the time distribution of average cash flows from development and production;
- size of an economic deposit in terms of ore reserve tonnage;
- metal product mix realized from an economic deposit;

- step-by-step assessment of the undiscounted development and production phase components of the unit cash flow for an economic deposit.

The last of these indicators is intended to reveal specific facets of mineral resource quality. The step-by-step procedure, outlined in table 1, expresses results in average or expected dollars per tonne of ore from economic discoveries.

Gross-in-situ value, the product of geological grades and metal prices, reflects the expected geological grade of an economic deposit. Mining losses account for the part of geological reserves which is inevitably left behind in pillars and remnants. Also, geological grades are diluted by the mining of barren or low-grade waste rock adjacent to the deposit itself. These mining losses are a function of such facets of deposit quality as deposit size, ore width, depth below surface, and geotechnical properties.

Milling losses evaluate the incomplete recovery of the metal content of the mill feed in the concentrate product. For example, in the milling process, the recoverable ore delivered to the mill, which might contain 2 percent copper and 5 percent zinc, may be upgraded to produce a 20-percent copper concentrate and a 55-percent zinc concentrate, with the loss of 10 percent of the copper content and 20 percent of the zinc content in the tailings. Milling losses depend on the mineralogical characteristics of the deposit.

Table 1

AVERAGE DEVELOPMENT AND PRODUCTION PHASE COMPONENTS
OF CASH FLOW FOR AN ECONOMIC DEPOSIT
(\$ per tonne of ore)

Gross In-Situ Value	
Less: Mining Losses	
Milling Losses	
Smelting and Refining Charges	
Concentrate Transportation Costs	
Revenue at the Minesite	
Less: Pre-Production Capital Expenditures	
Production Costs	
Cash Flow	

In determining the value of the concentrate products, smelting and refining charges have to be deducted. The combined effect of these charges may be illustrated by expressing the market value of metal contained in the concentrate as a percentage of the refined metal price. Thus, the revenue received for copper in concentrate form might represent 70 percent of the copper price, while 50 percent of the zinc price might be paid for zinc contained in a zinc concentrate. Typically, gold and silver byproducts contained in base metal concentrate realize in the order of 90 percent of their refined prices. Thus, smelting and refining charges are a function of the mix of metals found in a deposit.

Concentrate transportation costs then have to be deducted, as shown in table 1, to work the valuation back to an estimate of revenue at the minesite. Transportation costs depend on the geographical location of a deposit in relation to the smelting facilities.

Revenue at the minesite normally represents the top line of a cash flow calculation associated with the contemplated development of a mineral deposit. The costs associated with producing the concentrate then have to be deducted. These include the pre-production capital expenditures required to develop the necessary capacity and the production costs incurred in operating the mine. Capital and operating costs are a function of virtually all aspects of the quality of the mineral resource input.

The year-by-year deduction of capital and operating cost estimates from revenue at the minesite results in a time distribution of potential or before-tax cash flow. The cash flow distribution is then combined with an estimated cost of capital to derive more complete productivity measures reflecting the average return characteristics for an economic deposit.

Summing Up

The methodology outlined in this chapter results in evaluations of several absolute measures of total factor productivity. The dynamic component of this evaluation procedure concerns the geological characteristics associated with the mineral resource input. Real exploration expenditure trends, estimated year by year over the historical period of study, are incorporated in the appraisal. The mineral deposits discovered as a result of those expenditures are classified by discovery date and the economic consequences of their particular geological features are assessed.

All of the other labour, capital, and inter-industry factors of production are held constant. The cost of capital is fixed. Development- and production-phase cash flows for each of the historical discoveries, apart from the influence of their geological characteristics, are evaluated on the basis of a standard set of present-day economic and technological conditions.

This somewhat hypothetical procedure enables us to isolate the effects of changes in the mineral resource input on the total factor productivity of mining. In seeking explanations for the time trends evaluated, the two main geological components of mining productivity - exploration expenditures and mineral resource quality - are subjected to more detailed examination.

4. CANADA'S BASE METAL RESOURCES: THE DATA BASE

The evaluation procedure developed is now applied to assess geological aspects of productivity change in Canada's base metal mining sector.²⁶

Contribution of Base Metal Mining

Base metal resources have played an integral part in the growth and development of mining in Canada. The constituent commodities - copper, zinc, lead, molybdenum, and byproduct gold and silver - require similar exploration, development, and production technologies, and form a consistent grouping in terms of sources of information.

During the first half of this century, Canadian base metal supply was derived primarily from three major mineral deposits - the Sullivan zinc-lead mine in southern British Columbia, the Flin Flon copper-zinc-silver mine in northern Manitoba, and the Horne copper-gold mine in northwestern Quebec. Base metal supply in the period since the second world war has been characterized by rapid growth and extensive geographical diversification. Discoveries and developments of importance include copper-gold deposits in the Chibougamau region of Quebec; the Brunswick orebody and other zinc-lead-copper deposits in the Bathurst region of New Brunswick; the Geco copper-zinc-silver mine in northern Ontario; copper-zinc deposits in northern Manitoba; base metal deposits in the Mattagami and Noranda regions of Quebec; large low-grade copper and copper-molybdenum deposits in British Columbia; the Pine Point complex in the Northwest Territories; the Kidd Creek zinc-copper-lead mine in the Timmins region of Ontario; the Anvil zinc-lead-silver mine in the Yukon; and base metal deposits at Nanisivik and Polaris in the high Arctic.

Value of production from the base metal sector increased from \$2.2 billion in 1975 to \$4.1 billion in 1980. The prolonged world-wide recession then drove prices and output down to \$3.0 billion per year in 1982 and 1983, before rebounding to \$4.2 billion in 1984. The further anticipated recovery in base metal markets during 1985 has not been apparent to mid-year.

The base metal sector accounts for 40-45 percent of the value of Canada's metallic mineral production. Canada ranks first in the world as

26. For further information on the data base outlined here, see B.W. Mackenzie, Economic Mineral Exploration Targets, Working Paper No. 28, Centre for Resource Studies, Kingston, January 1984, 63 pp.

a producer of zinc, third in silver, molybdenum and gold, and fourth in copper and lead.²⁷

Copper and zinc are the two most valuable constituents of Canada's base metal resources. Production of these two metals is impressive. Cumulative Canadian output to 1984 is 22.8 million tonnes of copper and 29.5 million tonnes of zinc, valued at \$43.6 billion and \$38.4 billion respectively using mid-1985 prices.

Base metal mining is a particularly interesting subject for examining the geological aspects of productivity. As outlined, Canada's base metal resources have been intensively and extensively explored, developed, mined, and exhausted. However, undiscovered base metal deposits are masked by a relatively complex set of geological conditions. The question is whether the resulting time trends in geological characteristics associated with the discovery of economic base metal deposits are having a positive or a negative effect on mining productivity change.

Study Specifications

The case study concerns 274 significant base metal deposits discovered in Canada to 1977, classified by discovery date. In the final stage of analysis, these discoveries are grouped into three main geological categories; *volcanic-associated*, *sediment-hosted*, and *porphyry* deposits, to provide a more consistent basis for comparison.

The geological aspects of mining productivity are examined by considering time trends in exploration expenditures, the number of economic deposits discovered, and the geological and economic characteristics of those discoveries. Thus, the 65 significant deposits discovered prior to 1946 are distinguished from the 209 discoveries made during the modern era of base metal exploration, the 32-year period 1946-77. The 1946-77 period is further subdivided into two 16-year and four 8-year intervals for analysis purposes.²⁸

All money values are expressed in constant 1983 dollars. The gross national expenditures implicit price index is used to inflate historical data to 1983-dollar equivalents.

27. Traditionally, about 20 percent of Canada's copper production is a byproduct of nickel mining. Approximately 95 percent of its silver production and 30 percent of its gold production have been derived as byproducts from base metal mining.

28. While the selected time intervals are somewhat arbitrary, they are intended to provide a balance between the need for a sufficient number of intervals to detect time changes, and the requirement for a sufficient sample size of discoveries within each interval.

As discussed in chapter 3, the economic viability of each deposit is evaluated on the basis of a standard set of current economic and technological outlook conditions. An economic deposit is defined as a discovery which realizes a total revenue of at least \$20 million and a rate of return of at least 8 percent. The \$20 million minimum size insures that any deposit of significance is included in the evaluation.²⁹ The 8-percent rate-of-return investment margin has been selected as our best estimate of the weighted average cost of capital for mineral investment funds.³⁰

Exploration Expenditures

Estimates of total base metal exploration expenditures are required for each time interval of interest. The intention is to include all costs associated with searching for and delineating the possible economic discoveries of interest including, of course, unsuccessful exploration expenditures. Such expenditures are difficult to estimate, mainly because government statistics are too aggregated to be directly applicable.

The base metal exploration expenditure estimates used in the study are based on annual Statistics Canada data for metallic mineral exploration expenditures. To derive relevant estimates, exploration expenditures for metallic minerals that are excluded from the study, particularly for

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29. The size of a deposit may be measured in a number of ways. Ore reserve tonnage and recoverable metal content are indicators which neglect grades and prices on the one hand, and prices on the other. Such criteria as cash flow and net present value combine size and profitability considerations. Total revenue over mine life (i.e., net smelter return price times recoverable metal content valued at the minesite) provides a helpful economic measure of deposit size as distinct from profitability. This is the measure of deposit which is used throughout the study.
30. The weighted average cost of capital in constant money terms is comprised of the costs of individual sources of funds. Sources of funds may be simply grouped into two types - debt and equity. Considering inflation and taxation effects, debt capital represents a low cost source of funds, with constant money after-tax costs normally in the range of 1 to 3 percent. The cost of equity funds typically varies from 6 to 15 percent. The financial structure of a mining company - basically how much debt and how much equity it utilizes - is then applied to cost estimates for the individual sources to assess the weighted average cost of capital. The 8-percent weighted average cost of capital assumed in this study should be viewed within this framework.

nickel, uranium, gold, silver, tungsten and iron ore, have been deducted from the metallic mineral totals.³¹

These base metal exploration expenditures, totalling approximately \$3.5 billion, are summarized in table 2 by time interval. A high rate of growth in exploration is evident until the early sixties with a generally constant level of expenditure since then. Consequently, about two-thirds of total exploration costs have been incurred in the second half of the 1946-77 period.

Table 2

TOTAL EXPLORATION EXPENDITURES
(\$ 1983 million)

1946-77 period	3,492
By time interval:	
1946-61	1,107
1962-77	2,385
1946-53	256
1954-61	851
1962-69	1,222
1970-77	1,163

A \$4-million annual exploration budget has been chosen as an efficient level for an exploration organization. This size of budget is considered large enough to afford the best possible exploration skills and technology, and small enough to encourage a high degree of motivation

31. The base metal exploration expenditure data have been assembled from various government and corporate sources on a continuing basis since 1972. A description of the method of estimation and sources of information is given in appendix II, Effect of Taxation on Base Metal Mining in Canada, B.W. Mackenzie and M.L. Bilodeau, Centre for Resource Studies, Queen's University, 1979. Further discussion may be found in B.W. Mackenzie and R. Woodall, "Economic Productivity of Base Metal Exploration in Australia and Canada", paper presented at International Institute for Applied Systems Analysis, Laxenburg, Austria, December 1983, revised February 1984, 64 pp.

and organizational efficiency.³² The budget rate is used to estimate the average time for an exploration organization to discover an economic deposit.

Possible Economic Discoveries for Evaluation

A total of 274 discoveries which could possibly satisfy economic deposit conditions are selected for evaluation. The distribution of these possible economic discoveries among time intervals is presented in table 3. The deposits are listed in appendix I, classified by geological type and by discovery date.

32. The assumption of a \$4-million most-efficient annual exploration budget is a subjective judgment based on discussions with exploration personnel and the opportunity to observe both successful and unsuccessful exploration at work. Opinions on this subject, of course, vary. While the \$4-million figure may be criticized, there is little doubt that the most efficient exploration budget lies within the range of \$2 million to \$8 million per year. Results from a study of metallic mineral discoveries in Canada as a function of exploration budget size for the 1958-73 period, converted below to 1983 Canadian dollars, supports this view.

<u>Annual Exploration Budget</u>	<u>Percentage of Exploration Expenditures</u>	<u>Percentage of Economic Discoveries</u>
>\$8 million	44	15
\$4-8 million	14	35
\$2-4 million	13	40
<\$2 million	29	10

See P.A. Bailly, "Changing Rates of Success in Metallic Exploration", paper presented at Geological Association of Canada annual meeting, Vancouver, April 1977.

If exploration budgets are too small, the exploration organization will be unable to mount a modern, efficient, and competitive program. At the other extreme, a hazard arises as companies with larger budgets typically develop organizations where procedures become formalized and bureaucratic styles are permitted to develop. More discussion and sensitivity analysis illustrations on this point may be found in B.W. Mackenzie and R. Woodall, "Economic Productivity of Base Metal Exploration in Australia and Canada", paper presented at International Institute for Applied Systems Analysis, Laxenburg, Austria, December 1983, revised February 1984, 64 pp.

The sensitivity of relative time changes in mining productivity to the exploration budget rate would be an interesting area for further work.

Table 3

POSSIBLE ECONOMIC DISCOVERIES FOR EVALUATION

Total	274
Pre-1946	65
1946-77 period	209
By time interval:	
1946-61	89
1962-77	120
1946-53	40
1954-61	49
1962-69	68
1970-77	52

The intention is to include all known base metal deposits which offer medium-term potential for development. Deposits are classified by discovery date. A discovery is considered to be made when the deposit which ultimately forms the basis for mine development is first encountered by drilling. Deposits are treated individually if their discovery required essentially independent primary exploration programs.

Of the total number of deposit, 209 were discovered during the thirty-two year period 1946-77. There appears to be a significant increase in discovery rate until the mid-1960s, followed by a modest decline. While the 65 pre-1946 discoveries cannot be included in our overall analysis of mining productivity, they are used to provide a more complete picture of the time trend in the quality of base metal resources.

General Market Estimates

General market estimates are made to evaluate the time distribution of revenues for each of the possible economic discoveries.

Metal prices are both the most important and the most uncertain variables in the assessment of cash flows. Therefore, while study results initially assume an expected set of prices, cash flows are also evaluated as a function of price. For this purpose, the expected price outlook is

bounded by upper- and lower-limit prices for each mineral commodity. The prices used are shown in table 4.³³

Table 4

LONG TERM METAL PRICE PROJECTIONS
(U.S. dollars)

Metal	Price Basis	Lower-Limit Prices	Expected Price	Upper-Limit Price
Copper	per pound metal	.85	1.05	1.30
Gold	per ounce metal	400	550	800
Lead	per pound metal	.25	.35	.45
Molybdenum	per pound in con.	4.50	6.00	10.00
Silver	per ounce metal	10	13	20
Zinc	per pound metal	.45	.60	.70
Exchange Rate	US \$ per C \$	.95	.80	.70

These estimates are long-term average price projections, the period of which is intended to correspond to the timeframe of the three-phase mineral supply process being evaluated. Since the prices are only applied in the final production phase, the relevant time period extends from about 10 years to 50 years into the future.

The price estimates presented in table 4 and used in the time trend assessments may be considered optimistic in terms of present price levels and in terms of current market projections which tend to be correlated with the recent past. However, there will in fact be little relationship between prices 10 to 50 years hence and the currently prevailing conditions.

In this study, it is the relative changes in mining productivity over time, not the absolute economic values, which are of prime importance. Thus, the long-term metal prices projected, held constant in each case, are not so critical. However, since time trends in productivity may be a function of the level of market prices, the relative productivity changes are examined for a wide range of possible future prices.

33. The basic United States dollar price estimates have been combined with exchange rate estimates so as to give the widest possible Canadian dollar price range. The correlation between metal prices and the exchange rate has not been considered. This correlation would have the effect of increasing the US \$ per C \$ exchange rate as a function of metal prices.

The assessment of costs and revenues assumes that metal concentrate is produced at each possible mine. General net smelter return conditions for copper, lead and zinc concentrates are used to convert the forecast metal prices to a revenue estimate for the sale of concentrate at the smelter.³⁴ Concentrate transportation charges are then deducted to work the smelter payment back to a minesite value.

Individual Deposit Estimates

Individual deposit-by-deposit estimates of recoverable ore reserves, ore capacity, preproduction period, preproduction capital cost, the cost of major modifications, sustaining capital, operating cost, metallurgical recoveries, concentrate grades, and concentrate transportation, have been calculated for each of the possible economic discoveries, based on present-day economic and technological conditions. These deposit estimates utilize actual historical data and feasibility study estimates to the extent available. Otherwise, generalized Canadian costing relationships are applied, reflecting an order-of-magnitude level of accuracy.³⁵

With respect to processing facilities, where more than one deposit of the same type exists in a region, deposits are evaluated assuming utilization of a common mill facility. The overall regional mill capacity is specified, as is the distance between the deposit and the mill. The deposit is allocated a proportion of the mill capital cost based on relative capacities. The distance is used to estimate a road-haulage transportation cost for the ore. Additional road construction may be specified.

Actual deposit data and feasibility study estimates have mainly been obtained directly from the mining companies concerned. General sources

34. The net smelter conditions for copper, lead and zinc concentrates are based on the worldwide survey and analysis of approximately 200 actual smelter contracts by Lewis and Streets. See: P.J. Lewis and C.G. Streets, "An Analysis of Base-Metal Smelter Terms", in the Proceedings of the Eleventh Commonwealth Mining and Metallurgical Congress, Hong Kong, 1978, Institution of Mining and Metallurgy, London. A number of modifications have been made based on discussions with marketing personnel to adapt their general results to more specific Canadian conditions.
35. For examples of this type of generalized deposit costing procedure, see T.A. O'Hara, "Quick Guides to the Evaluation of Orebodies", CIM Bulletin, February 1980, pp. 87-99; A.L. Mular, Mining and Mineral Processing Equipment Costs and Preliminary Capital Cost Estimation, special volume 25, The Canadian Institute of Mining and Metallurgy, 1982, 265 pp.; B.W. Mackenzie, "Generalized Deposit Costing Relationships", pp. 438-458 in Economic Guidelines for Exploration Planning, course notes, Department of Geological Sciences, Queen's University, 1985, 608 pp.

of deposit information include Energy, Mines and Resources Canada mineral inventory cards, the Financial Post Corporation Service, the Northern Miner library, and published reports and papers.

Data Base Critique

There are two inherent limitations in the data base assembled for this study. First, possible economic deposits are classified on the basis of their discovery dates. There is an uncertain time lag between primary exploration expenditures and discovery. This means that exploration expenditures included in the assessment of cost characteristics for one time interval may result in discoveries included in the following time interval. This is particularly important if possible economic deposits are thereby excluded from the overall time period being assessed. For this reason, two discoveries made shortly after the end of the 1946-77 study period have been included in the evaluation.

Secondly, the completeness and reliability of individual deposit data is a function of discovery date; i.e., the data base for older mines is more comprehensive than that available for more recent discoveries. This is especially important with respect to ore reserve estimates, since development and production typically proceed on the basis of partial delineation results. Our objective has been to include as complete an estimate as possible for the tonnage and grade characteristics of each deposit. Nevertheless, there is a tendency to undervalue cash flows, particularly for mines discovered most recently. This bias is most significant with respect to tonnage. The problem can be eased by periodic updating and improvement of the data base.

The importance of these two data base limitations to overall results depends on the length of the time period and the proximity of the end of the period to the present. The thirty-two-year time period chosen for this study is considered to be of sufficient duration to keep these effects within tolerable limits. Furthermore, information has been assembled several years after the end of this period. Nevertheless, some degree of bias certainly still exists.

These and other shortcomings in the data base reflect a compromise between the availability of data and the research limitations imposed by time constraints. There is much room for improvement. However, we feel that the margin of error which may exist in the analysis is not large enough to affect the reliability of the overall results and conclusions.

5. GEOLOGICAL ASPECTS OF MINING PRODUCTIVITY IN THE BASE METAL SECTOR: AN OVERVIEW

This chapter examines the combined effects of all geological characteristics on productivity change in base metal mining.

Base Case Conditions

The base case conditions, which are used as a standard of comparison with other results, are:

- all possible economic deposits discovered in Canada during the period 1946-77;
- expected metal price conditions;
- \$20 million minimum acceptable total revenue for an economic deposit;
- 8-percent minimum acceptable rate of return for an economic deposit;
- \$4-million annual exploration budget.

Under these conditions, 96 of the 209 base metal deposits discovered during the 1946-77 period are found to be economic. The cost and revenue characteristics of these 96 deposits are used to assess the time distribution of average cash flows for an economic deposit through exploration, development and production phases. Mining productivity measures are derived from these cash flow estimates.

The expected value per economic discovery is evaluated as \$110 million at the start of exploration. This means that, on average, based on the assumed conditions, \$110 million of new wealth or economic surplus is associated with the discovery of an economic base metal deposit. Alternatively, the productivity of base metal mining may be expressed as an 18-percent expected rate of return in relation to an assumed 8-percent cost of capital. These results indicate that the base metal sector has the potential to increase substantially the net value or wealth available to Canadian society. They also show that, for the assumed conditions, base metal resources in Canada are of a high quality.

Metal Price Variants

Mining productivity assessments are presented in table 5 as a function of lower-limit, expected, and upper-limit price conditions. These findings illustrate the high degree of sensitivity of mining productivity in the base

Table 5

PRODUCTIVITY OF BASE METAL MINING: METAL PRICE VARIANTS

	Number of Economic Discoveries	Expected Value per Economic Discovery (EV, \$ million)	Expected Rate of Return (percent)
Lower-limit prices	22	-37	4
Expected prices	96	110	18
Upper-limit prices	151	270	31

metal sector to price uncertainties. The sector is shown to be decidedly uneconomic at lower-limit prices. As metal prices rise, there are sharp increases in the number of economic discoveries, the expected value per economic discovery, and the expected rate of return. At the same time, higher metal prices reduce the average exploration expenditure and the average time required to discover and delineate an economic deposit.

Thus, absolute measures of productivity based on single point metal price projections are extremely fragile. Also, relative changes in productivity with time evaluated for one set of prices, may not hold for other possible price levels.

Time Trends

Assuming expected metal price conditions, table 6 shows the variations in base metal mining productivity which have occurred with time relative to the overall 1946-77 period averages. According to the methodology adopted, these represent the economic consequences of changes in the geological characteristics of the mineral resource input, the resultant of exploration expenditure trends and the changing quality of base metal resources revealed by discovery.

Table 6

TIME TRENDS IN BASE METAL MINING PRODUCTIVITY ARISING FROM CHANGES IN GEOLOGICAL CONDITIONS: EXPECTED PRICES

	Number of Economic Discoveries	Expected Value per Economic Discovery (EV, \$ million)	Expected Rate of Return (percent)
1946-77 period	96	110	18
By time interval:			
1946-61	42	83	18
1962-77	54	121	18
1946-53	16	187	27
1954-61	26	35	13
1962-69	27	174	20
1970-77	27	65	14

The economic discovery rate appears to have held up well, for the specified conditions, increasing from the late-1940s to the mid-1950s and then remaining more-or-less constant. This roughly corresponds to the pattern of exploration expenditures (table 2).

It is difficult to discern time trends in the productivity indicators. A comparison of results between the two 16-year intervals suggests that while the profitability of the base metal supply process has tended to remain constant, as indicated by the expected rate of return, the average size of the economic deposits discovered has increased significantly, as reflected by the higher expected value per economic discovery during the most recent 1962-77 interval.

Results for the four 8-year time intervals are more erratic. A severe deterioration in productivity is evident from 1946-53 to 1954-61, coming back to above-period values for the 1962-69 interval, before falling off once again during 1970-77. The evidence presented here suggests a decline in expected rate of return over the study period.

The use of a larger number of shorter time intervals was not found to be helpful. Results were found to be more irregular but not otherwise appreciably different than those presented in table 6. Nevertheless, it would be interesting to carry out a formal statistical analysis of time trends based on results for a variety of time-interval assumptions.

Finally, we would like to see how the time trend variations for expected metal prices shown in table 6 compare with corresponding results

for the lower-limit and upper-limit price levels. The expected value per economic discovery (EV) is used to illustrate this relationship, findings being illustrated in figure 3.

In some ways, the three patterns of productivity variation shown in figure 3 are similar. For example, 1946-53 and 1962-69 stand out in all cases as being the two best intervals. More importantly, there is a noticeable general shift in the direction of the long-term productivity trends as a function of metal prices. While the trend at expected prices appears to be flat, there is a long-term decline in productivity at lower-limit prices and somewhat of an improvement at upper-limit prices. This suggests that the geological and economic characteristics of more recent discoveries are more sensitive to metal price than those made earlier in the 1946-77 period. The higher degree of sensitivity may result from an increasing proportion of base metal discoveries of marginal quality. In any case, the main message here is that caution should be exercised in generalizing from mining productivity results based on any particular set of actual or projected commodity prices.

A general observation from both table 6 and figure 3 is that, in the long term, changes in mining productivity associated with the mineral resource input are neither gradual or systematic. Even crudely grouping the large sample size of historical experience assembled within 8-year time intervals, the variations are quite erratic. Despite the application of scientific concepts and increasingly sophisticated exploration technology, there appear to be large fluctuations in geological conditions with time.³⁶ This reflects the economic consequences of two important geological features of base metal resources:

- the highly variable nature of resource quality among economic deposits;
- the high risk nature of mineral exploration and, consequently, the somewhat random character of economic discoveries.

Thus, long-term trends in productivity change associated with the geological characteristics of mineral resources are not easy to detect. The more detailed examination which now follows of the geological components embodied in these overall productivity measures will hopefully provide some useful insights concerning these time trends.

36. These time trends do not take into account the real changes in mineral market conditions or the improvements in mining and mineral processing technologies which have taken place during the respective study periods. In our evaluation, these factors are standardized on the basis of current outlook conditions. The intention is to isolate those aspects of mining productivity which have resulted from the changing nature of the exploration process and from changes in mineral endowment characteristics as revealed through the base metal deposits discovered.

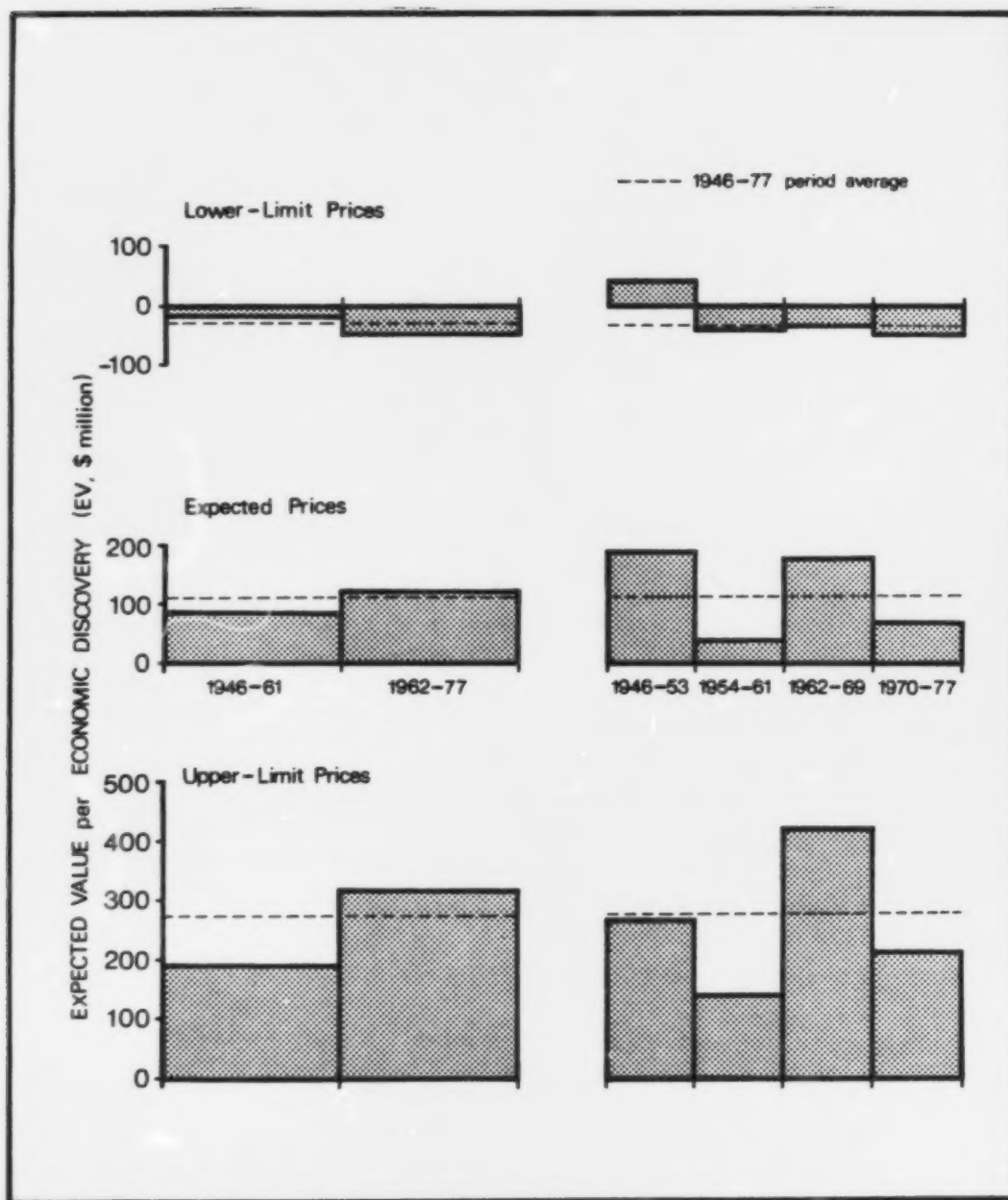


Figure 3. Time Trends in the Expected Value per Economic Discovery Arising from Changes in Geological Conditions

6. THE EXPLORATION EXPENDITURE COMPONENT OF BASE METAL MINING PRODUCTIVITY

One of the two geological components of productivity change in base metal mining - mineral exploration expenditures - is appraised in this chapter.

Trends in this exploration component of productivity are measured by the following indicators:

- average undiscounted exploration expenditure per economic discovery, determined by dividing total exploration expenditures (table 2) by the number of economic discoveries assessed (for example, from tables 5 and 6);
- average exploration period required to find and delineate an economic deposit, evaluated as the average undiscounted exploration expenditure per economic discovery divided by the \$4-million annual exploration budget rate considered;
- average exploration expenditure per economic discovery expressed as a discounted value at the start of exploration (E), using the assumed 8-percent cost-of-capital discount rate.

Using these measures, the effects of changing discovery rates on exploration expenditures is implicitly taken into account by expressing exploration costs as averages per economic deposit discovered.

Time trends in these exploration expenditures indicators are presented in table 7 for expected metal price conditions.

For the overall 1946-77 study period, the \$36-million average undiscounted exploration expenditure per economic discovery, invested at the rate of \$4 million per year, indicates an average exploration period of 9 years, and a discounted exploration expenditure of about \$25 million. These findings suggest relatively easy and efficient exploration conditions by international standards. For example, a recent study based on a similar data base, methodology, and assumptions found that an economic base metal deposit in Australia costs four times as much and takes four times as long to find and delineate as one in Canada.³⁷

37. See B.W. Mackenzie and R. Woodall, "Economic Productivity of Base Metal Exploration in Australia and Canada", paper presented at International Institute for Applied Systems Analysis, Laxenburg, Austria, December 1983, revised February 1984, 64 pp.

Table 7

TIME TRENDS IN THE EXPLORATION COMPONENT OF BASE METAL MINING PRODUCTIVITY: EXPECTED PRICES
(per economic deposit discovered)

	Average Undiscounted Exploration Expenditure (\$ million)	Average Exploration Period (years)	Average Discounted Exploration Expenditure (E, \$ million)
1946-77 period	36	9	25
By time interval:			
1946-61	26	7	20
1962-77	44	11	29
1946-53	16	4	13
1954-61	33	8	23
1962-69	45	11	29
1970-77	43	11	28

Time trends in these indicators of exploration cost are of particular interest. Exploration activity during the study period grew from a relatively small base, the 1946-53 interval accounting for only 7 percent of total exploration expenditures for the period (table 2). Average exploration expenditures per economic discovery increased markedly from the first to the second half of the study period. Table 7 shows a doubling of economic discovery costs from 1946-53 to 1954-61, followed by a more modest rise to the 1962-69 interval. However, average exploration expenditures do not appear to have increased since the early 1960s.

Time trends in the average discounted exploration expenditure per economic discovery (E) as a function of possible future metal price levels are illustrated in figure 4. Higher prices are shown to reduce the average exploration expenditures and time required to discover and delineate an economic deposit. This is because more discoveries satisfy the "economic deposit" definition, and not because of an integral change in the exploration process.

In general terms, the three time trends of average exploration expenditures shown in figure 4 are similar. At all price levels, there is a significant increase in average expenditures from 1946-61 to 1962-77 and, more specifically, a sharp rise between the 1946-53 and 1954-61 time intervals. A modest increase in economic discovery costs is indicated

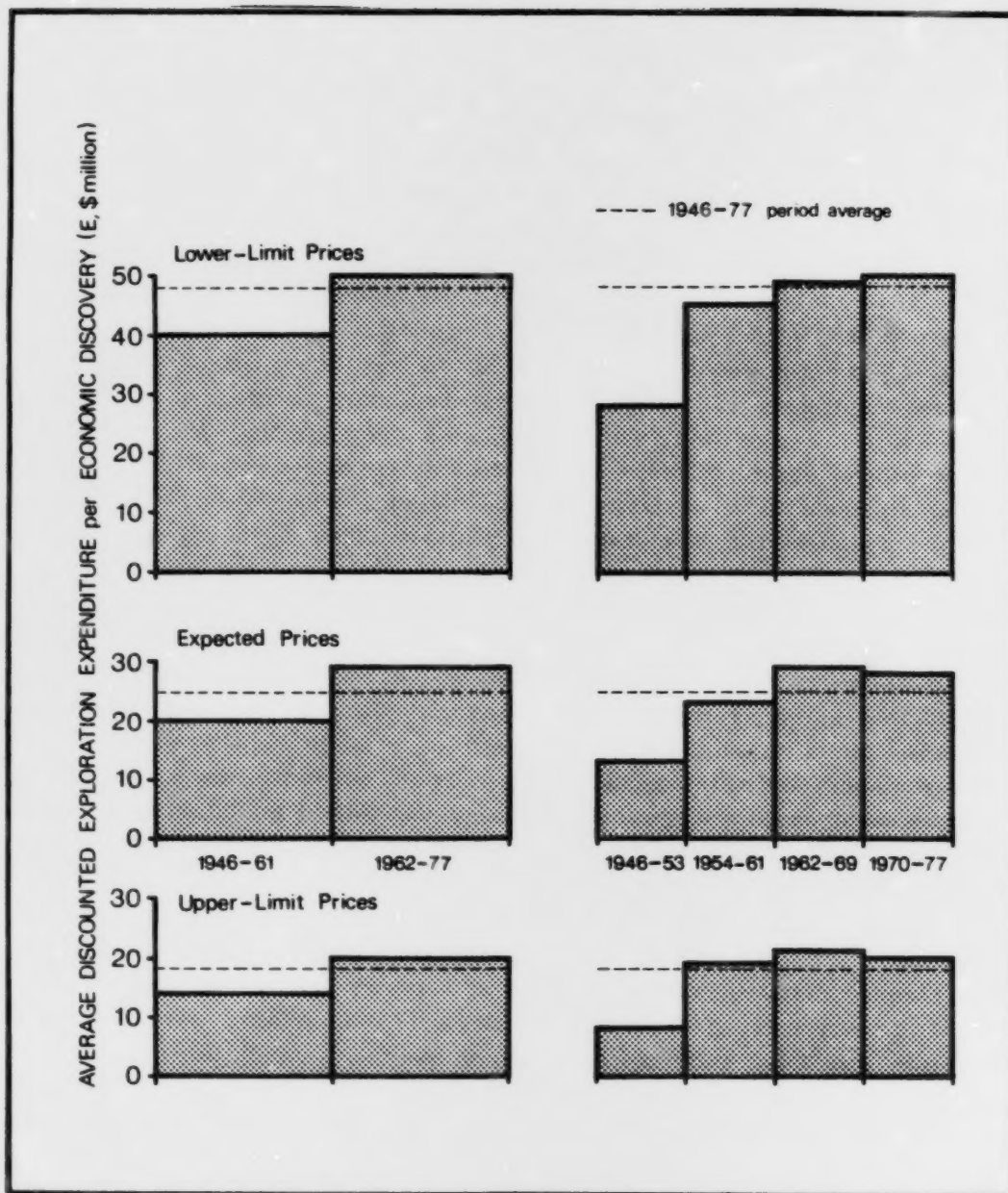


Figure 4. Time Trends in the Average Discounted Exploration Expenditure per Economic Deposit Discovered

from 1954-61 to 1962-69 with no discernable increase since then. The number of economic deposits evaluated for the more recent intervals appears to be somewhat more sensitive to metal prices than the number estimated for the earlier intervals.

What dynamic forces have shaped the exploration expenditure component of base metal mining productivity presented in table 7 and figure 4?

The 1946-77 study period corresponds to the modern era of mineral exploration in Canada. The 65 significant base metal deposits discovered prior to 1946 (table 3) generally outcropped and were found, therefore, by prospectors searching for surficial deposits using fairly primitive methods. Since the second world war, these traditional prospecting skills have been increasingly integrated with improving geological concepts, more scientific exploration techniques, and deep drilling technology to discover buried deposits where the bedrock is concealed.

One dynamic force at work during this period has been depletion in the form of increasing exploration difficulty. The discovery of mineral deposits is a practical illustration of sampling without replacement. The discovery of 274 significant base metal deposits to 1977, even from mineral resources as extensive and abundant as Canada's, must have exacted a price in terms of lowering the probability of economic discovery and, thereby, increasing average discovery costs. Consequently, the locus of exploration tends to shift with time both to greater depths and to more remote regions, further increasing exploration expenditures. For example, base metal exploration expenditures in the Yukon and Northwest Territories increased from 4 percent to 13 percent of the Canadian total from 1946-61 to 1962-77.

Secondly, there have likely been real changes in the unit costs of labour and inter-industry inputs to exploration during the study period. These factors include changes in wage and salary rates, and the costs of contract geophysical, geochemical, geological and drilling services, and exploration materials and supplies, which are not attributable to depletion, technological advances, or inflation. For example, the real cost of fuel increased dramatically in the early 1970s. These more general economic changes warrant further attention.

The third and final dynamic force considered is technology. Advances in geological concepts and exploration technology have likely had an important impact on lowering economic discovery costs. New methods take time to catch on. After a new concept or technique is proven to work in a particular case, it becomes more popular and is used more broadly, increasing the frequency of finding certain types of deposit.

Relatively rapid and cheap airborne *electromagnetic methods*, which became available in the late 1940s and early 1950s, were able to penetrate the glacial concealment over large areas. The effectiveness of applying this new technology, followed by drilling the highest priority *anomalies* defined, is reflected in the low average discovery costs which characterize the 1946-53 interval. The sharp build-up in average economic discovery costs from 1946-53 to 1954-61 may have resulted from more intensive application of essentially the same airborne geophysical and drilling technologies and programs to second, third, and fourth priority anomalies. The fact that average exploration expenditures have not increased since the early 1960s suggests that the application of better conceptual models for area selection and the ranking of targets, together with refinement and new development in exploration technologies, have been successful in countering the rising costs associated with depletion.

The explanatory factors offered here should only be regarded as suggestive. There is a need to develop an improved understanding of depletion effects, real changes in unit costs, and exploration research and development in relation to exploration expenditure trends.

7. THE QUALITY OF BASE METAL RESOURCES

Examination of the second geological component of productivity change in base metal mining - the quality of base metal resources discovered - is introduced here. This is done by evaluating and comparing the development and production phase characteristics of economic deposits as a function of their discovery date.

Base Case Conditions

Base case conditions, evaluating all possible economic deposits discovered in Canada during the 1946-77 period using expected metal prices, are once again used as a standard for comparison.

Under these conditions, 96 of the 209 base metal deposits are economic. The cost and revenue characteristics of these 96 deposits are averaged to determine the time distribution of average cash flows for an economic deposit. Various productivity measures outlined in chapter 3 are derived from these development- and production-phase cash flow estimates.

The expected return from development and production for an economic deposit is found to be \$272 million, expressed as a discounted value at the start of development.³⁸ This is equivalent to a potential or before-tax rate of return of about 34 percent. The expected or average size of an economic deposit is estimated to be 54 million tonnes of ore. Zinc accounts for 51 percent of the value of these deposits, copper for 24 percent, silver for 10 percent, lead for 9 percent, and gold and molybdenum for 3 percent each.

With regard to the expected cash flow components for an economic deposit, the gross in-situ value, reflecting geological grade, is \$193 per tonne. Mining losses represent \$24 per tonne, milling losses \$29, smelting and refining charges \$46, and concentrate transportation costs \$9 per tonne of ore. Thus, the revenue at the minesite is \$85 per tonne ($\$193 - 24 - 29 - 46 - 9 = \$85$ per tonne). Pre-production capital costs represent \$12 per tonne, and production costs \$35 per tonne. Thus, the potential or before-tax cash flow is \$38 per tonne of ore ($\$85 - 12 - 35 = \$38$ per tonne).

38. It is important to note that our examination of mining productivity from here on, unlike the results presented in chapters 5 and 6, makes no allowance for exploration time and cost. Attention is restricted to the development and production phases because the focus is on the quality of mineral resources discovered.

Time Trends I

While the 65 significant base metal deposits discovered before 1946 cannot be considered in our overall assessment of mining productivity, they are included here to provide a more complete picture of the changing quality of resources.

Tables 8 and 9 compare the average quality and cash flow components of the 17 pre-1946 discoveries evaluated as economic for expected price conditions with the 96 economic deposits found during the period 1946-77. It is interesting to note that, while 46 percent of the 210 discoveries considered for the 1946-77 period satisfy economic deposit conditions, only 26 percent of the 65 deposits discovered prior to 1946 do so.

Table 8

AVERAGE QUALITY OF AN ECONOMIC DEPOSIT: EXPECTED PRICES,
TIME TRENDS I

	Discovery Date	
	Pre-1946	1946-77
Number of economic deposits	17	96
Return (\$ million)	564	272
Rate of return (percent)	59	34
Deposit size (t million)	21	54
Product mix (percent):		
Zinc	37	51
Copper	17	24
Silver	14	10
Lead	14	9
Gold	18	3
Molybdenum	-	3

Table 9

**AVERAGE CASH FLOW COMPONENTS OF AN ECONOMIC DEPOSIT:
EXPECTED PRICES, TIME TRENDS I
(\$ per tonne of ore)**

	Discovery Date	
	Pre-1946	1946-77
Gross in-situ value	240	193
Mining losses	36	24
Milling losses	37	29
Treatment charges	46	46
Transportation costs	6	9
Revenue at the minesite	115	85
Capital expenditures	13	12
Production costs	38	35
Cash flow	64	38

The following significant points arise from the results presented:

- economic discoveries made before 1946 are found to be significantly more profitable on average than those discovered during the 1946-77 period. The effects of the preeminent Sullivan, Flin Flon, and Horne deposits on the average results for this pioneering era are no doubt substantial;
- the average size of an economic deposit for the period 1946-77 is two-and-a-half times greater than for the pre-1946 discoveries. This large difference likely reflects the discovery of a changing mixture of deposit types, and particularly the increasing influence of very large porphyry deposits;
- the average mix of metals associated with the economic discoveries is also shown to have changed significantly. The proportion of precious metals byproducts is much higher for the pre-1946 period (32 percent vs. 13 percent), indicating the discovery of a relatively large share of polymetallic volcanic-associated ores. On the other hand, the combined zinc and copper share has risen from 54 to 75 percent of the total value, suggesting an increasing proportion of porphyry copper and sedimentary-hosted zinc-lead discoveries;

- table 9 indicates that the falling off in profitability is mainly the result of lower average ore grades. The gross in-situ value per tonne of ore drops by approximately one-fifth from the pre-1946 discoveries to those made during 1946-77;
- the growing importance of open pit mining is likely the main reason for the reduction in mining losses shown;
- the improvement in milling losses may be partly explained by the decline in average ore grades and partly by the shift towards porphyry and sedimentary-hosted deposits which are characterized by less-complex mineralogy, enabling higher milling recoveries to be achieved than for the volcanic-associated ores;
- smelting and refining charges appear to have remained unchanged;
- the increase in transportation costs probably reflects the increasing remoteness of discoveries in relation to smelter locations;
- both unit capital expenditures and unit production costs are marginally lower for the economic deposits discovered during the 1946-77 period. Thus, the cost-reducing effects of the larger average size of deposits and more open pit mining appear to be largely offset by the increasing depth and remoteness of other more-recent discoveries;
- the resulting decline in the potential or before-tax cash flow per tonne of ore is consistent with the falling off in discounted returns shown in table 8.

Time Trends II

Tables 10 and 11 break down the overall experience for the thirty-two year study period into two 16-year intervals, 1946-61 and 1962-77. The pre-1946 assessments are retained for comparative purposes.

The main findings arising from this second set of time trends are summarized as follows:

- the average size of the economic deposits found in the 1962-77 interval is about five-times larger than for the 1946-61 economic discoveries. The main reason for this order-of-magnitude difference is the influence of several extremely large porphyry deposits discovered in the mid- to late-1960s.

Table 10

AVERAGE QUALITY OF AN ECONOMIC DEPOSIT: EXPECTED PRICES,
TIME TRENDS II

	Discovery Date		
	Pre-1946	1946-61	1962-77
Number of economic deposits	17	42	54
Return (\$ million)	564	171	350
Rate of return (percent)	59	30	36
Deposit size (t million)	21	17	82
Product mix (percent):			
Zinc	37	53	50
Copper	17	19	27
Silver	14	15	8
Lead	14	8	9
Gold	18	5	2
Molybdenum	-	-	4

- the most recent economic discoveries are also shown to be more profitable on average. This is surprising because the economics of the large porphyries are relatively marginal. The higher average profitability of the 1962-77 economic discoveries can only be explained by the superiority of non-porphyry deposits discovered during this interval, including the singular Kidd Creek deposit found in 1963;
- with respect to the metal products recovered from economic deposits, there has been a significant build up in the proportion of copper and molybdenum, and corresponding reductions in copper, silver and gold shares, continuing the trend which starts with the pre-1946 discoveries. This once again illustrates the increasing role of porphyry deposits, and a relative decline in the importance of volcanic-associated ores;

Table 11

AVERAGE CASH FLOW COMPONENTS OF AN ECONOMIC DEPOSIT:
 EXPECTED PRICES, TIME TRENDS II
 (\$ per tonne of ore)

	Discovery Date		
	Pre-1946	1946-61	1962-77
Gross in-situ value	240	194	185
Mining losses	36	24	21
Milling losses	37	29	28
Treatment charges	46	46	45
Transportation costs	6	9	10
Revenue at the minesite	115	86	81
Capital expenditures	13	12	12
Production costs	38	35	34
Cash flow	64	39	35

- a comparison of unit cash flow components for the 1946-61 and 1962-77 time intervals in table 11 shows a marginal falling off with time in ore grade (gross in-situ value), minesite revenue and, consequently, before-tax cash flow. These results do not appear consistent with the discounted return results shown in table 10. If grade, unit revenue, and before-tax cash flow per tonne of ore have decreased, why is the expected rate of return higher for the most recent time interval? The reason for this apparent inconsistency arises from differential discounting effects for high-grade and low-grade deposits. The high-grade deposits tend to be relatively small and, thus, have short productive lives, typically only a few years. On the other hand, the low-grade deposits are generally large, supporting mine lives in the order of 15-30 years. The greater proportion of high-grade ores in the early production years has the effect of increasing profitability indicators such as rate of return relative to the average undiscounted cash flow values over mine life.

Time Trends III

In this section, results for the 1946-77 study period are further disaggregated into four 8-year intervals as summarized in tables 12 and 13.

Table 12

AVERAGE QUALITY OF AN ECONOMIC DEPOSIT: EXPECTED PRICES, TIME TRENDS III

	Discovery Date				
	Pre-1946	1946-53	1954-61	1962-69	1970-77
Number of economic deposits	17	16	26	27	27
Return (\$ million)	564	272	109	485	214
Rate of return (percent)	59	38	25	41	28
Deposit size (t million)	21	18	16	131	34
Product mix: (percent)					
Zinc	37	60	44	32	70
Copper	17	11	29	44	7
Silver	14	17	11	10	5
Lead	14	11	5	3	16
Gold	18	1	11	3	2
Molybdenum	-	-	-	8	-

Table 13

AVERAGE CASH FLOW COMPONENTS OF AN ECONOMIC DEPOSIT:
 EXPECTED PRICES, TIME TRENDS III
 (\$ per tonne of ore)

	Discovery Date				
	Pre-1946	1946-53	1954-61	1962-69	1970-77
Gross in-situ value	240	228	191	146	223
Mining losses	36	30	29	15	27
Milling losses	37	34	29	19	36
Treatment charges	46	56	42	37	54
Transportation costs	6	9	6	8	12
Revenue at the minesite	115	99	85	67	94
Capital expenditures	13	11	13	10	13
Production costs	38	39	34	25	41
Cash flow	64	49	38	32	40

Significant points arising from this final set of time trends are:

- expected return and rate of return characteristics of economic discoveries deteriorate from 1946-53 to 1954-61, improve for the 1962-69 interval, and then fall off once again for the most recent 1970-77 interval. No systematic overall time trend is apparent;
- the serious decline in return characteristics for the 1954-61 interval, symptomatic of depletion effects, may result from the more intensive application of an exploration technology that was essentially unchanged from that used in the 1946-53 interval to lower priority targets;
- the influence of large low-grade economic porphyry deposits is shown to be mainly concentrated in the interval 1962-69. This is illustrated by the high expected return and average deposit size for the interval, as well as by the relatively large proportions of copper and molybdenum in the product mix. The high expected rate of return for 1962-69 once again appears to contradict the notion that porphyry deposits are not generally very profitable. However, other high-grade and more profitable discoveries are likely influential

here, such as the Kidd Creek discovery in 1963 and the Ruttan deposit discovered in 1969;

- the greater proportions of zinc and lead in the metal mix for economic deposits discovered during 1970-77 points to the increased importance of sedimentary-hosted deposits. This trend may also explain the large average size of these most recent discoveries, second only to that of deposits discovered in the 1962-69 interval;
- time series results for gross in-situ value per tonne indicate that there has been no methodical falling off in average ore grades. The decrease in grade shown for 1954-61 and, particularly for the 1962-69 interval, reflect the influence of the economic porphyry deposits. The average ore grade for the most recent 1970-77 interval is essentially the same as at the start of the time period;
- the poorer average grades of the economic deposits discovered in 1954-61 and 1962-69 are partially compensated for by lower unit mining and milling losses, reduced treatment charges, and lower unit capital expenditures and production costs. Thus, the before-tax cash flow per tonne of ore for these two intervals does not decline as markedly;
- the generally increasing trend in concentrate transportation costs reflects the increasing remoteness of economic deposits relative to established smelting and refining facilities;
- once again, differential time value effects for high-grade and low-grade deposits explain apparent inconsistencies between the discounted return values in table 12 and the undiscounted unit cash flows in table 13. For example, the discrepancy between the relatively low before-tax cash flow per tonne and the high expected rate of return for economic discoveries during the 1962-69 interval is caused by the large proportion of high-grade ores in the early production years of the time distribution of average cash flows.

Metal Price Variants

Finally, we would like to test the more general validity of these time trends as a function of assumed metal prices.

Figure 5 compares variations in the average return per economic deposit discovered as shown in tables 8, 10, and 12 for expected prices

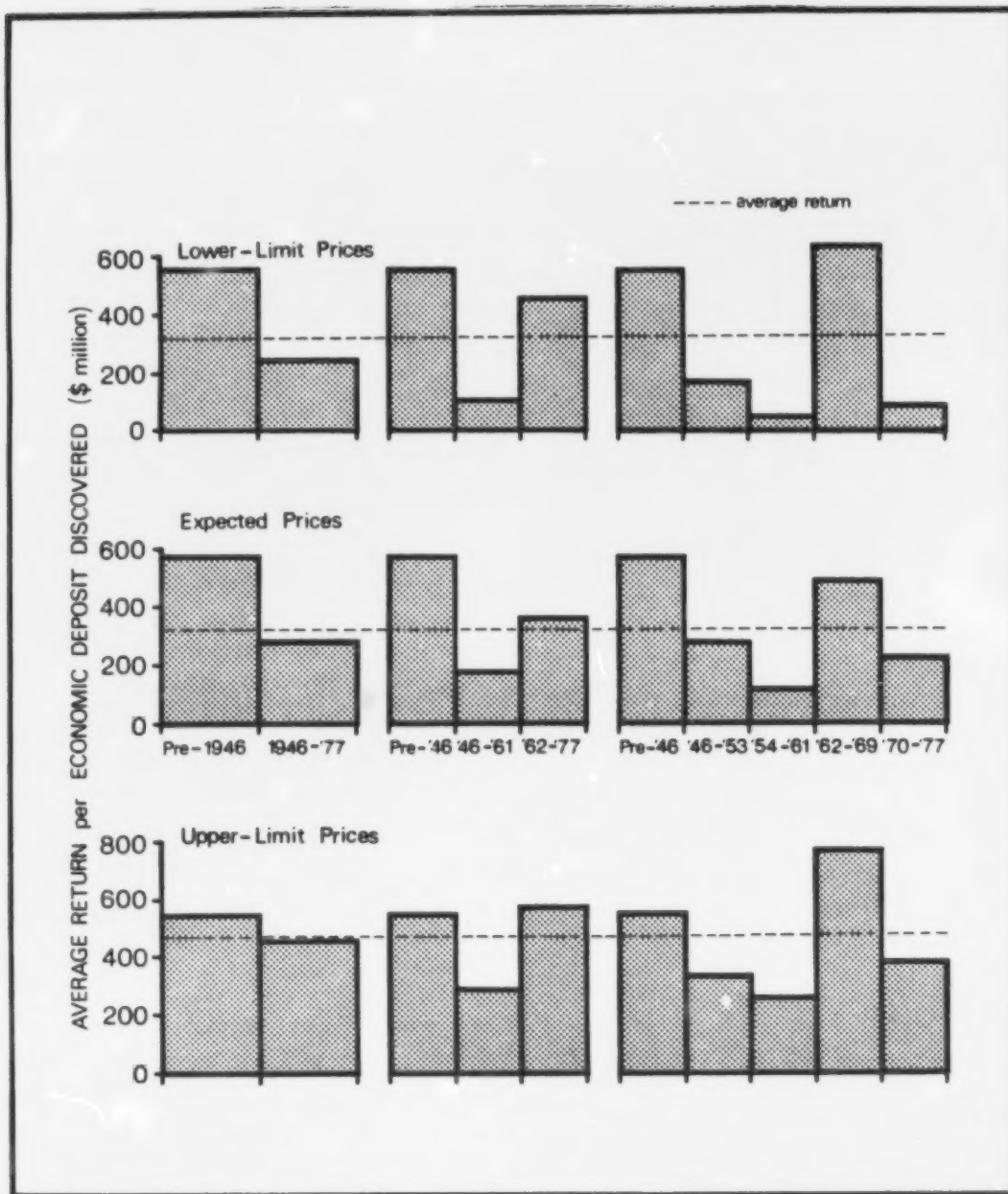


Figure 5. Time Trends in the Average Return per Economic Deposit Discovered

with corresponding results for the lower-limit and upper-limit price levels. The three time trends are similar. The pre-1946 and 1962-69 economic discoveries yield the highest average returns throughout. This mainly reflects the inclusion of the Horne, Flin Flon, and Sullivan deposits in the former interval and the Kidd Creek deposit in the latter. Average returns for the pre-1946 economic deposits are consistently higher than those for the discoveries made during the 1946-77 study period. On the other hand, the return characteristics which typify the 1962-77 interval are shown to be superior to those made earlier during 1946-61. Considering the four 8-year time intervals, average returns do not appear to have declined with time. In fact, the time trend seems to become positive as metal prices are increased to the upper-limit level. Once again, this indicates that the economic return characteristics of the more recent discoveries are more sensitive to price than those made earlier in the 1946-77 period.

Time trends in the average cash flow per tonne of ore are presented in figure 6 as a function of metal price, generalizing from the findings shown in tables 9, 11, and 13. The superior quality of the pre-1946 economic discoveries is confirmed, particularly at lower-limit prices. However, below-average unit cash flows are realized for the 1962-69 interval as compared to the above-average total returns illustrated in figure 5. Once the influence of deposit size is removed by expressing results per tonne of ore, the marginal character of the large porphyry deposits becomes apparent. Notably, unit cash flow values for the most recent 1970-77 interval are the equal of those for all economic deposits discovered.

Summing Up

No systematic trend is apparent in the quality of base metal resources discovered during the 1946-77 period. If economic deposits discovered prior to 1946 are included in this examination, a decline in the expected return and rate of return productivity indicators may be discerned. In view of the long timeframe considered, any falling off in the average return characteristics of economic deposits and, hence, decline in the productivity of base metal mining in Canada, is much more gradual than is generally believed.

The findings presented here show a high degree of variability in results among the individual time intervals. These fluctuations are of course what make it so difficult to detect long-term productivity trends. Such variations are partly a result of the high-risk random element

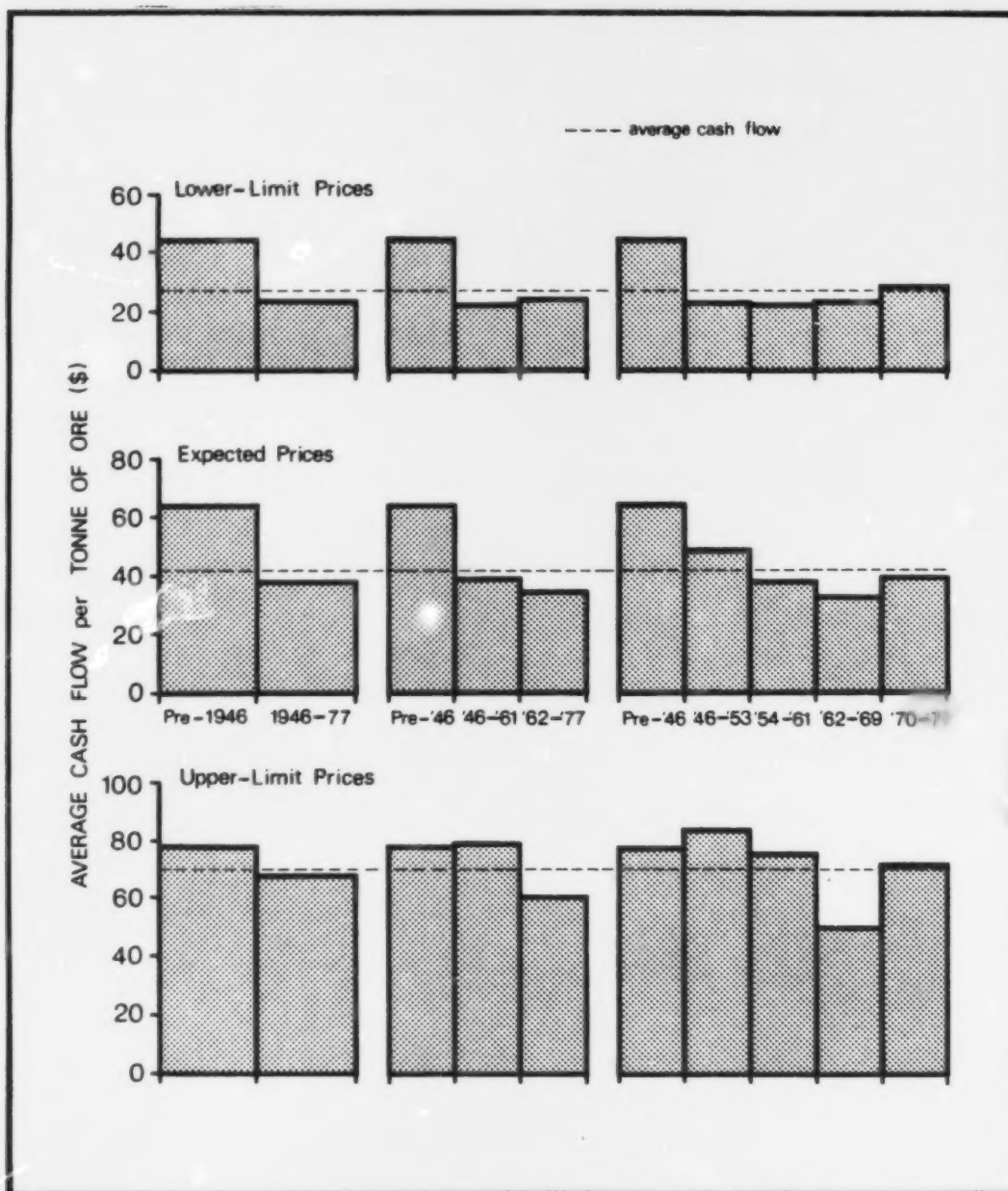


Figure 6. Time Trends in the Average Cash Flow per Tonne of Ore

inherent in the mineral exploration and discovery process. In addition, as the foregoing explanations suggest, the variations are also caused by the diverse quality and changing mixture of geological deposit types. To remove this second influence, time trends in the quality of base metal resources are now examined by grouping discoveries into geologically consistent categories.

8. CLASSIFICATION OF BASE METAL RESOURCES BY DEPOSIT TYPE

In order to reduce the variability in study results among individual time intervals, the present chapter disaggregates base metal resources into more geologically consistent categories.

Deposit Type Classification

Mineral deposit types reflect specific geological settings. Exploration is directed towards those types of deposit which are perceived to be most economically attractive.

In order to obtain a more geologically consistent view of the changing quality of resources, base metal deposits are classified here into three main types: volcanic-associated massive sulphide, sedimentary-hosted massive sulphide, and porphyry deposits.

Volcanic-associated massive sulphide deposits are defined by three major characteristics: occurrence of mineralization in a stratiform zone of massive sulphides; association with extrusive submarine volcanic rocks; and deposition of the ore from the discharge waters of submarine hot springs. Volcanic-associated deposits are typically small and high grade. Occurring in active tectonic zones at intervals through the entire geological time frame, volcanic-associated deposits are found in the Canadian shield, appalachian, and cordilleran environments.

Sedimentary-hosted massive sulphide deposits are defined on the basis of their association with sedimentary host rocks, typically shale or carbonate marine sediments. Sedimentary-hosted zinc-lead deposits, which may contain copper and silver, are usually of medium size and grade, occurring in sediments formed since about 2,000 million years ago. This deposit type is mainly found in the Canadian appalachian and cordilleran environments.

Porphyry deposits are invariably related, both spatially and genetically, to highly fractured and hydrothermally altered zones in complex high level felsic intrusions within active tectonic belts. Porphyry deposits are typically large and low grade, and may contain copper only, copper-gold, copper-molybdenum, or molybdenum with or without tungsten. This deposit type tends to be identified with relatively young rocks, especially mesozoic-tertiary active zones such as the Canadian cordilleran environment.

The 274 base metal discoveries included in the study are classified in appendix I by deposit type. The "other" category of deposits includes chibougamau-type, skarn, red bed copper, breccia pipe, native copper in

basalt, and copper and molybdenum vein-type deposits. Lead-zinc-silver vein deposits are excluded from the data base.

The Quality of Base Metal Resources as a Function of Deposit Type

Tables 14 and 15 compare indicators of the quality of economic deposits among the three base metal types for expected metal price conditions. The average return from development and production, expressed as a discounted value at the start of development, is shown to be remarkably similar among the deposit types considered, varying from

Table 14

AVERAGE QUALITY OF AN ECONOMIC DEPOSIT BY TYPE: EXPECTED PRICES

	Volcanic- Associated Deposits	Sedimentary- Hosted Deposits	Porphyry Deposits
Number of economic deposits	63	24	11
Return (\$ million)	163	212	177
Rate of return (percent)	53	42	23
Deposit size (t million)	16	44	298
Product mix (percent):			
Zinc	47	72	-
Copper	25	-	69
Silver	15	7	4
Lead	4	21	-
Gold	9	-	7
Molybdenum	-	-	20

Table 15

AVERAGE CASH FLOW COMPONENTS OF AN ECONOMIC DEPOSIT
 BY TYPE: EXPECTED PRICES
 (\$ per tonne of ore)

	Volcanic- Associated Deposits	Sedimentary- Hosted Deposits	Porphyry Deposits
Gross in-situ value	254	192	29
Mining losses	35	19	1
Milling losses	41	26	4
Treatment charges	55	60	4
Transportation costs	9	13	1
Revenue at the minesite	114	74	19
Capital expenditures	15	9	2
Production costs	43	29	8
Cash flow	56	36	9

\$163 million for the economic volcanic-associated deposits to \$212 million for the sedimentary-hosted deposits. Further examination shows that this similarity is due to the cancelling out of strikingly different size, grade and profitability characteristics.

Sixty-three of the 145 volcanic-associated massive sulphide discoveries recorded to 1977 have been evaluated as economic, including, for example, the Brunswick deposits, Buchans, Corbet, Flin Flon, Fox, Geco, Goldstream, Horne, Kidd Creek, Lynx, Mattagami, Norbec, Normetal, Que-mont, Ruttan, Selbaie, and Sturgeon. Economic deposits of this type are characteristically small and high grade, as shown by the average deposit size and gross in-situ value per tonne indicators in tables 14 and 15, although a select few are large. Zinc and copper are generally the most important constituent metals, but appreciable precious metals are often present as well, averaging almost one-quarter of the total product value. Volcanic-associated deposits, once found and delineated, tend to be very profitable, the potential rate of return for an economic discovery averaging 53-percent for the assumed conditions.

Twenty-four of the 41 sedimentary-hosted massive sulphide deposits found to 1977 satisfy economic deposit conditions, including Faro, HB, Howards Pass, Nanisivik, Newfoundland Zinc, the Pine Point complex of deposits, Polaris, and Sullivan. These deposits, which yield mainly zinc and lead with a minor silver byproduct, are usually of medium size and

medium-high grade, although, once again, the occasional discovery such as Howards Pass and Sullivan is large. Economic sedimentary-hosted deposits, somewhat less profitable than the volcanic-associated ores, nevertheless typically offer handsome before-tax rates of return, averaging 42 percent.

The 11 economic porphyry deposits, evaluated from a total of 29 significant discoveries recorded, are characterized by their very large size and very low grades. These economic discoveries include Afton, Bell, Bethlehem, Brenda, Endako, Highmont, Island Copper, and Lornex. While copper and molybdenum predominate in the product mix, there also may be an appreciable precious metal content, shown in table 14 to average more than one-tenth of the overall product value. These deposits are typically much less profitable than the economic volcanic-associated and sedimentary-hosted discoveries, the rate of return from development and production averaging 23 percent.

Thus, base metal deposits classified by type exhibit distinctive geological and economic characteristics. It is not difficult to surmise that a changing mixture of deposit types would have a notable influence on the overall time trend results considered in the previous section. How has the role of these deposit types changed with time, and what factors explain the changes which have taken place?

The Changing Mixture of Deposit Types

Although mineral exploration is a long-term activity, it passes through fashionable phases such as gold in the 1930s, polymetallic copper and zinc deposits in the 1940s and 1950s, nickel and porphyry base metal deposits in the 1960s, sedimentary-hosted base metal deposits in the 1970s, and back to gold in the 1980s. These "fashion" periods, influenced by a number of factors, are mainly market driven. Non-fashionable commodities and deposit types appear for a time to be less attractive. Fashion influences long-term strategic planning because the selection of deposit types as exploration targets is based on highly uncertain judgments which vary with time. Changing emphasis in target selection and, therefore, in the allocation of exploration funds, ultimately results in changing proportions of actual discoveries among the base metal deposit types.

Time distributions of the number of economic base metal deposits discovered by type are presented in figure 7 as a function of metal prices. The most notable features of these distributions are:

- high and more-or-less uniform discovery rate for volcanic-associated deposits;

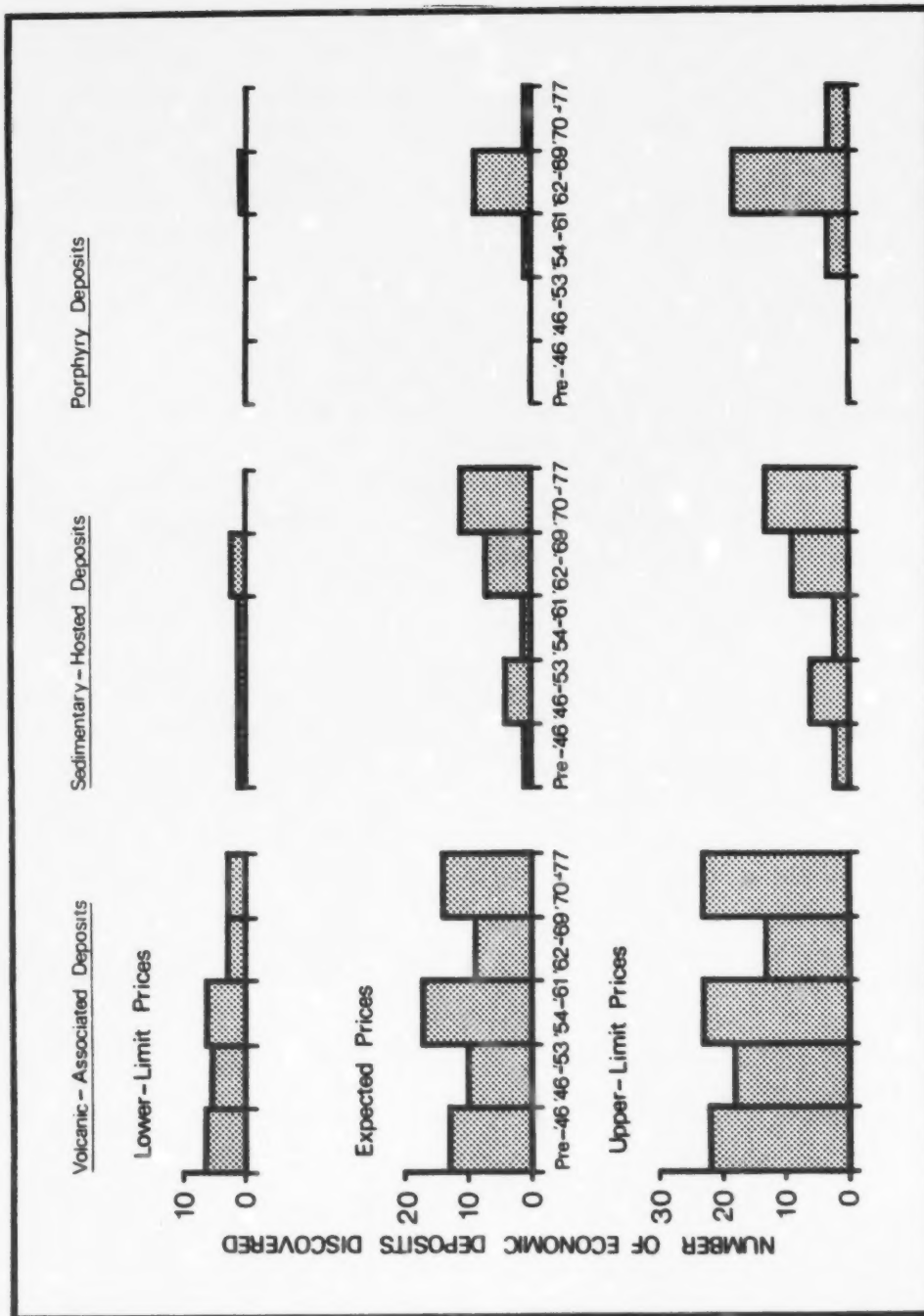


Figure 7. Time Distributions of Number of Economic Deposits Discovered by Type

- generally increasing number of sedimentary-hosted discoveries;
- concentration of economic porphyry discoveries in the 1960s;
- for all deposit types and time intervals, a high degree of sensitivity of the number of economic deposits to metal prices.

The following examples illustrate some of the factors which have influenced the relative importance of base metal deposit types in Canada. The advent of airborne geophysical techniques in the late 1940s and early 1950s stimulated the exploration and discovery of volcanic-associated massive sulphide deposits. A strong shift towards porphyry deposits in the 1960s was associated with buoyant copper and molybdenum market conditions (particularly concentrate markets in Japan), government tax incentives, and advances in the development of large-scale open pit and mineral processing technology, as well as geological recognition of the porphyry environment. The relative importance of sedimentary-hosted deposits in the 1970s has been influenced by improved conceptual geological models and relatively strong zinc markets. A more recent swing back to volcanic-associated exploration targets has been encouraged by the more-modest investment requirements and lower risk associated with the development of small high-grade mines, the market hedge provided by the polymetallic nature of the volcanic-associated ores, and high gold and silver prices.

While the changes in perception which influence the allocation of exploration funds among deposit types include geological factors, there is obviously a much broader range of technological and economic factors at work. The changing mixture of deposit types mainly reflects economic choice rather than either luck or geological necessity. In order to reveal what is happening beneath these diverse changes, time trends should be more specifically examined by deposit type, particularly in view of the quality differences noted in tables 14 and 15.

9. TIME TRENDS IN THE QUALITY OF BASE METAL RESOURCES BY DEPOSIT TYPE

Time trends results are presented in this final chapter as a function of deposit type to enable us to examine more consistently the changing quality of base metal resources and consequent effects on mining productivity. This analysis is carried out for volcanic-associated deposits, and for a somewhat restricted sedimentary-hosted deposit time series. Economic porphyry deposits, too few in number and too concentrated by discovery date for time series analysis (see figure 7), are isolated by their exclusion.

Volcanic-Associated Deposits

There have been a sufficient number of economic volcanic-associated massive sulphide deposits discovered throughout our timeframe of interest to retain the same intervals used for overall assessment of base metal resource quality in chapter 7 (figure 7). Mining productivity indicators are presented in tables 16 and 17 for expected price conditions.

Table 16

TIME TRENDS IN AVERAGE QUALITY OF AN ECONOMIC VOLCANIC-ASSOCIATED DEPOSIT: EXPECTED PRICES

	Discovery Date				
	Pre-1946	1946-53	1954-61	1962-69	1970-77
Number of economic deposits	13	10	17	9	14
Return (\$ million)	208	195	71	405	55
Rate of return (percent)	60	42	30	117	31
Deposit size (t million)	14	24	11	33	8
Product mix (percent):					
Zinc	26	60	53	47	46
Copper	29	11	18	35	28
Silver	9	18	14	16	19
Lead	2	10	6	1	2
Gold	34	1	9	1	5
Molybdenum	-	-	-	-	-

Table 17

TIME TRENDS IN AVERAGE CASH FLOW COMPONENTS OF AN ECONOMIC VOLCANIC-ASSOCIATED DEPOSIT: EXPECTED PRICES
(\$ per tonne of ore)

	Discovery Date				
	Pre-1946	1946-53	1954-61	1962-69	1970-77
Gross in-situ value	272	275	227	246	260
Mining losses	42	37	31	36	32
Milling losses	45	43	38	35	44
Treatment charges	51	65	52	56	54
Transportation costs	6	11	8	9	11
Revenue at the minesite	128	119	98	110	119
Capital expenditures	15	12	13	17	18
Production costs	41	46	38	42	51
Cash flow	72	61	47	51	50

Time series results for this more specific grouping of deposits are found to be more systematic than those presented in chapter 7 for all deposits. However, notable fluctuations remain, reflecting the random nature of exploration in terms of the varying quality of mineral deposits discovered. In particular, the presence of the Kidd Creek deposit, the best base metal deposit found in Canada to date, in the 1962-69 interval, has a pronounced effect on the average size and return characteristics as one of only nine deposits included. Once the size dimension of Kidd Creek is removed, it is interesting to note that this discovery does not have a noticeable influence on unit cash flow characteristics.

With regard to ore grades, there is little if any evidence of depletion effects. Average grades fall off somewhat to 1954-61 but have increased since then, approaching their pre-1946 level in the 1970-77 interval. Hence, the ore grades of volcanic-associated deposits have not been declining.

Modest overall increases in unit costs are discerned in table 17. These presumably reflect a falling off in the quality of base metal resources in terms of increasing remoteness and depth. It is surprising that the associated cost increases are not more significant. As a consequence of the grade and cost trends, the unit cash flow of economic volcanic-associated deposits declines to 1954-61, remaining essentially unchanged thereafter.

The very high gold content for the economic deposits discovered prior to 1946 is possibly related to the early prospecting methods employed. Prospectors, primarily looking for gold, may have discovered gold-rich base metal deposits by panning stream sediments, working their way to the source.

There are significant changes in the average return and rate of return productivity indicators, reflecting the combined effects of unit cash flow values, deposit size, and time value. In particular, a notable deterioration in these indicators until 1954-61 is apparent. However, average results for the 1962-69 interval, influenced by the Kidd Creek discovery, represent all-time highs.

Findings for the most recent 1970-77 interval are disappointing. One possible explanation is depletion effects in terms of smaller, less profitable economic discoveries. On the other hand, there is an inherent bias in the data base to undervalue the more recent discoveries. This tendency is strongest with respect to ore reserve tonnage or, in other words, average deposit size. Furthermore, the bias is no doubt particularly pronounced for volcanic-associated deposits, which are the most erratic and difficult to delineate of the three types considered. Thus, when the data base is updated in the course of time, it would be surprising if the 8-million tonne average deposit size estimated for the 1970-77 interval did not increase significantly. This would enhance, in turn, the average return and rate of return characteristics.

Generalizing from the expected price results shown in table 16, time trends in the average return per economic discovery are presented in figure 8 as a function of price. The average returns at lower-limit prices are higher than for expected prices because the superior characteristics of the very few deposits which remain economic outweigh the market price differential. Most importantly, the time patterns are consistent through the range of prices examined. The 1954-61 and 1970-77 intervals are typified by relatively low returns and the 1962-69 interval by a very high average return. If the influence of the Kidd Creek discovery in 1963 were to be smoothed across the two adjacent intervals, the overall time trend would be essentially uniform for all three metal price levels.

Similarly, figure 9 depicts time trends in the average cash flow per tonne of ore for lower-limit, expected, and upper-limit prices. The patterns are once again consistent. Removing deposit size and time value aspects of the evaluation of resource quality, the unit cash flow results are much less variable. A decline in the average cash flow per tonne of ore is apparent to 1954-61 but, since that time, this aspect of resource quality has modestly improved.

Volcanic-associated massive sulphide deposits in Canada represent the longest-standing, most intensively pursued type of exploration target,

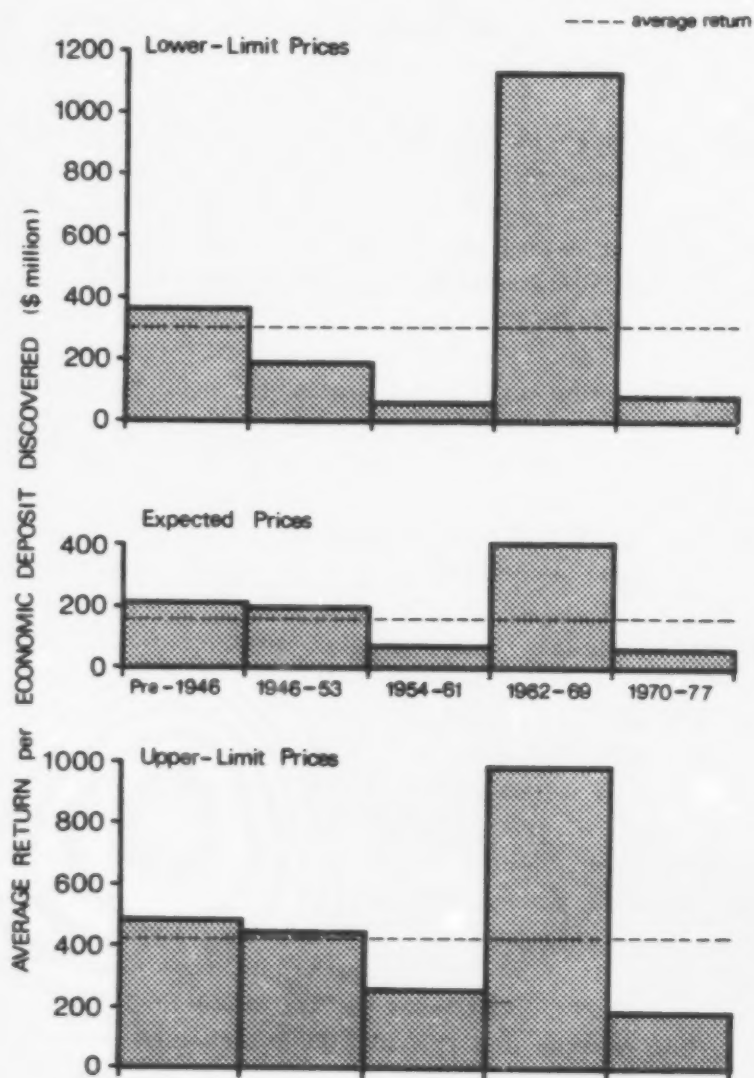


Figure 8. Time Trends in the Average Return per Economic Volcanic-Associated Deposit Discovered

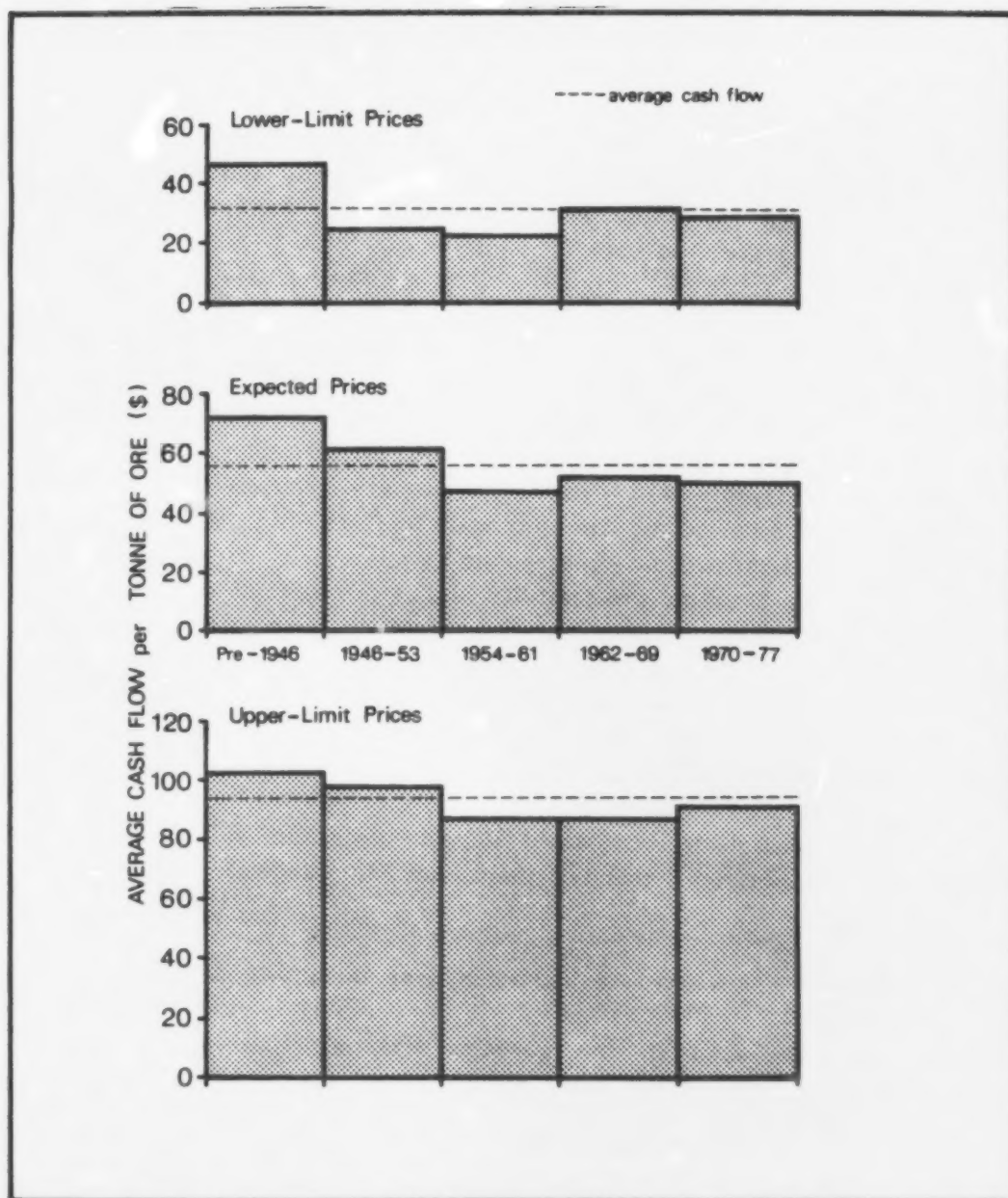


Figure 9. Time Trends in the Average Cash Flow per Tonne of Ore from Economic Volcanic-Associated Deposits

and one of the most mature exploration environments worldwide. This is illustrated by the fact that the Canadian environment yielded 152 significant discoveries to 1977. Hence, it may be surmised that the exhaustion of discovery possibilities for this deposit type, and consequent depletion effects, are relatively advanced. Nevertheless, little evidence can be found in the results presented here to support the contention that the quality of volcanic-associated ores is declining.

Sedimentary-Hosted Deposits

The number of economic sedimentary-hosted massive sulphide deposits is insufficient to enable meaningful assessments for all time intervals and metal price levels (figure 7). Thus, results are grouped for a 16-year interval, 1946-61, followed by the intervals 1962-69 and 1970-77. Also, attention must be confined to expected and upper-limit prices. For comparative purposes, average productivity indicators for all economic sedimentary-hosted deposits, including the pre-1946 discoveries, are also shown.

Time trends in the average quality and cash flow components of economic deposits for expected prices are presented in tables 18 and 19 respectively. The following significant points may be noted:

- this more geologically-consistent deposit grouping yields more systematic productivity trends than for all deposit types mixed together;
- the economic discovery rate increases over the study period;
- a marked increase in the average size of economic deposits is apparent, influenced in part by the inclusion of the very large Howards Pass discovery in the most-recent 1970-77 time interval;
- the metal product mix remains remarkably uniform. There is much less variability in this respect among sedimentary-hosted ores than among the volcanic-associated deposits;
- ore grades have not declined with time. The gross in-situ value per tonne of ore in the most recent interval is in fact found to be somewhat higher than the average for all economic sedimentary-hosted deposits;

Table 18

TIME TRENDS IN AVERAGE QUALITY OF AN ECONOMIC SEDIMENTARY-HOSTED DEPOSIT: EXPECTED PRICES

	Discovery Date			All Discoveries
	1946-61	1962-69	1970-77	
Number of economic deposits	5	7	11	24
Return (\$ million)	49	138	171	212
Rate of return (percent)	28	43	27	42
Deposit size (t million)	7	21	65	44
Product mix (percent):				
Zinc	79	73	78	72
Copper	-	-	-	-
Silver	7	6	3	7
Lead	14	20	19	21
Gold	-	1	-	-
Molybdenum	-	-	-	-

Table 19

TIME TRENDS IN AVERAGE CASH FLOW COMPONENTS OF AN ECONOMIC SEDIMENTARY-HOSTED DEPOSIT: EXPECTED PRICES
(\$ per tonne of ore)

	Discovery Date			All Discoveries
	1946-61	1962-69	1970-77	
Gross in-situ value	188	170	205	192
Mining losses	24	5	24	19
Milling losses	21	21	31	26
Treatment charges	58	61	61	60
Transportation costs	10	14	15	13
Revenue at the minesite	75	69	74	74
Capital expenditures	10	10	9	9
Production costs	27	25	34	29
Cash flow	38	34	31	36

- a modest increase in both unit losses and unit costs may be observed in table 19, reflecting the consequences of increasing remoteness, depth, and mineralogical complexity on the productivity of sedimentary-hosted base metal resources;
- a modest decline in cash flow per tonne of ore is indicated, resulting from the observed grade and unit cost trends;
- the high productivity of all sedimentary-hosted base metal resources taken together relative to results for the individual time intervals reflects the superior endowment characteristics of the initial pre-1946 discovery, the well-located Sullivan deposit. This is one instance where the highest quality deposit appears to have been discovered first;
- a rise from 1946-61 to 1962-69, followed by a fall from 1962-69 to 1970-77 in the average rate of return for the development and production phases.

Time trends in the average return and unit cash flow of economic sedimentary-hosted deposits as a function of metal price are illustrated in figures 10 and 11 respectively. The average return per economic deposit is shown to be increasing with time while the average cash flow per tonne of ore is declining. These time patterns are much more pronounced at upper-limit prices than at expected prices. Findings suggest that the increase in average deposit size reflected in the time trends of average returns more than offsets the falling off in other aspects of resource quality indicated by the declining unit cash flow trend.

Summing Up

A changing mixture of deposit types is associated with the historical pattern of base metal discoveries in Canada. These fluctuations and trends are mainly explained by a complex and uncertain set of actual and perceived economic conditions pertaining to the choice of deposit types for exploration. Therefore, time trends in the quality of base metal resources and the consequent effects on mining productivity may be most validly examined for specific deposit types.

The evidence presented in this chapter is incomplete. Time series analysis has been carried out for the volcanic-associated and sedimentary-hosted deposit types. The available evidence does not support the contention that the quality of Canada's base metal resources has deteriorated with time.

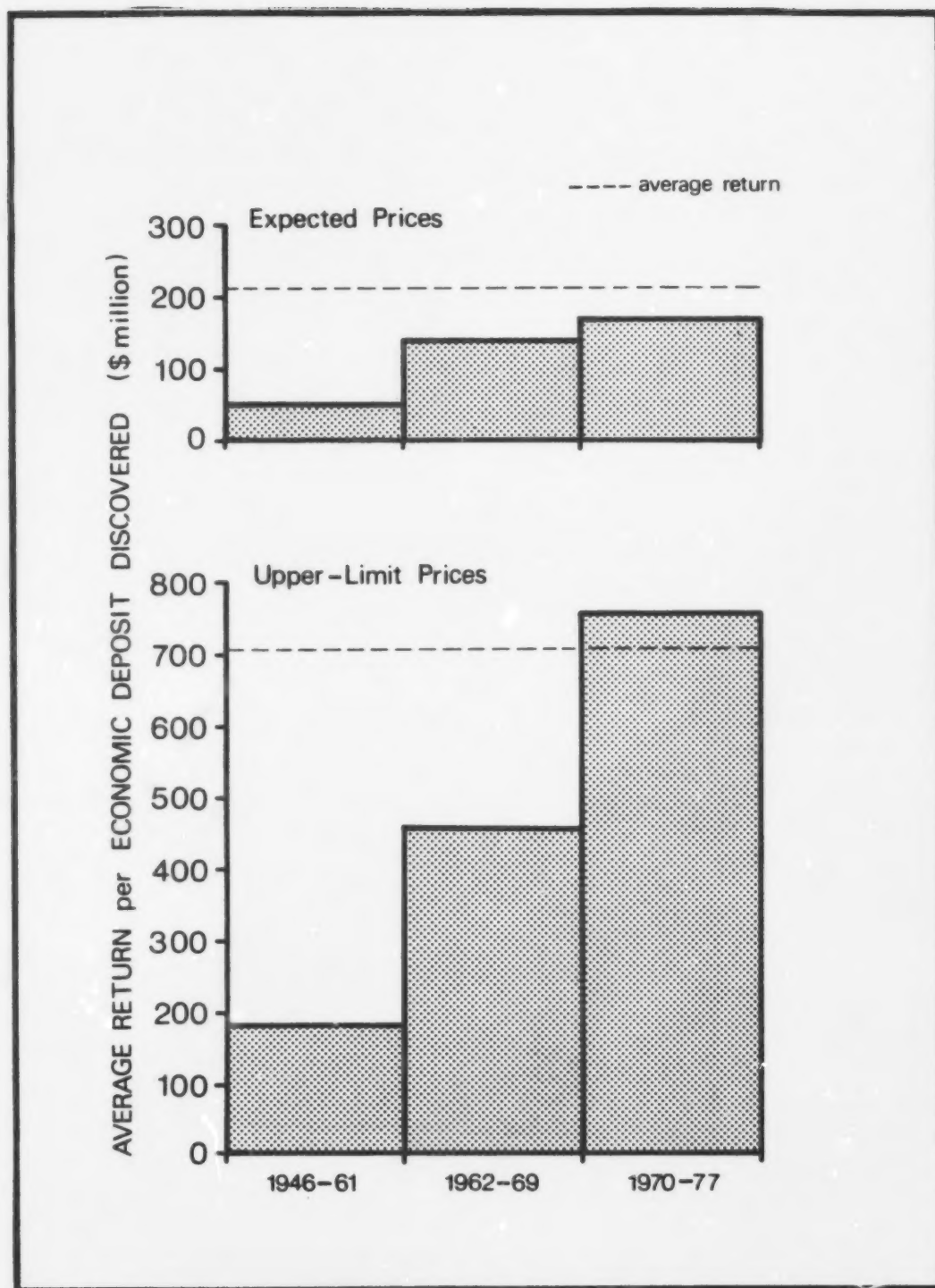


Figure 10. Time Trends in the Average Return per Economic Sedimentary-Hosted Deposit Discovered

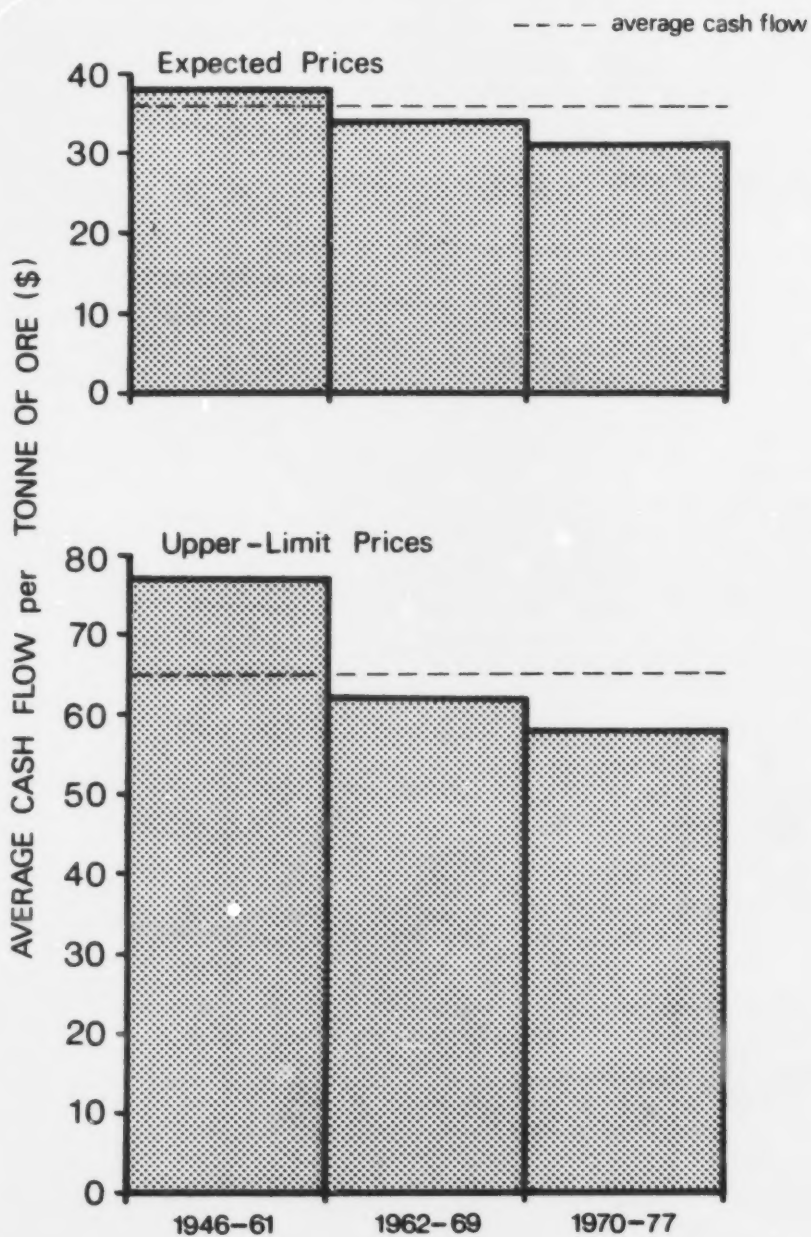


Figure 11. Time Trends in the Average Cash Flow per Tonne of Ore from Economic Sedimentary Hosted Deposits

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GLOSSARY

- Accounting:** system for recording financial data. Accounting records include an "income statement" which shows the sources of revenues and expenses over a period of time, and a "balance sheet" which tabulates accounts for a particular point in time to give values for the basic accounting equation: assets minus liabilities equal net worth. These records incorporate a number of non-cash elements such as depreciation charges, depletion allowances, and deferred taxes.
- Anomaly:** exceptional condition or circumstance, representing successful result of the broad reconnaissance stage of primary exploration. Anomalies may be indicated by geological, geophysical, or geochemical tests.
- Base Metals:** metals which the ancient alchemists tried to convert into gold and silver - usually they include copper, lead and tin. Today zinc is included in the group, partly because many mines produce zinc along with lead. For the same reason, we have included molybdenum in the case study, which is in some cases a byproduct of copper mining, and the gold and silver byproducts of base metal mining. Canada had no primary tin deposits of economic interest within the case study period.
- Capital Cost:** expenditure of funds on a project with the expectation of returning the invested funds and profits during future periods. Capital costs include expenditures for physical assets such as buildings and machinery, mine development costs, and working capital requirements. Capital costs embrace the initial installation of mining and mineral processing facilities during the preproduction period, as well as sustaining and other capital requirements during the productive mine life.
- Cash Flow:** difference between cash benefits (inflows) and cash costs (outflows) for a period of time. The first step in economic evaluation is to estimate the time distribution of cash flows for a project over its anticipated life.

Concentrate: saleable product obtained from initial processing (milling or concentrating) of a base metal ore. For example, a mining operation may produce a 25-percent copper concentrate which also contains gold, or a 60-percent lead concentrate with a silver byproduct.

Cost of Capital: cost of investment funds, derived from the composition of the capital available from different sources. The proportion of capital from each of these sources obtained at different costs is represented by a company's "weighted average of cost of capital". The explicit interest costs associated with debt sources of funds are combined with the implicit opportunity costs of equity sources for purposes of determining this cost of capital.

Cyclical Market Fluctuation: change in market conditions which is of a temporary nature arising, for example, from business cycles, changes in producer and consumer inventory levels, or strikes and other supply disruptions.

Discounted Cash Flow (DCF) Analysis: combines cash flow estimates for a project (representing the return on investment) with the time value of money (representing the cost of capital) to measure a project's economic worth for decision-making purposes. DCF criteria include net present value, and rate of return.

Discovery of a Mineral Occurrence: technical or geological success representing the successful result of primary exploration, most conveniently defined with respect to a particular decision point in the sequential exploration process. For example, the discovery of a mineral occurrence may be considered to take place when indications of mineralization and mineable widths are obtained in first-stage drilling, justifying selection of a target for the next exploration stage.

Economic Mineral Deposit: deposit which on evaluation satisfies specified minimum acceptable size and profitability conditions.

Electromagnetic (EM) Methods: type of geophysical exploration technique which uses an alternating electrical current above the earth's surface to induce a current to flow in any conductive deposit below it. The induced current creates its own alternating magnetic field which is measured in different ways to detect geophysical anomalies. Airborne EM methods have become very important in the early reconnaissance stage of base metal exploration.

Factors of Production: inputs required to produce goods or services, classically grouped into land, labour, and capital categories. Renewable and nonrenewable natural resources, including mineral deposits, comprise the land factor of production. Inter-industry inputs, including supplies, capital equipment, and services produced in other sectors of the economy, may be considered as a separate factor.

Geological Aspects of Mining Productivity: parameters directly associated with the mineral resource factor of production including the exploration expenditures required to find and delineate deposits, and the quality of the resources discovered.

Mill Capacity: scale of a mineral processing facility expressed in terms of the amount of ore which can be treated per unit time. Mill capacity may be specified by indicators such as tonnes per hour, tonnes per day, or tonnes per year.

Mill Recovery Factor: ratio of the amount of a valuable metal contained in a concentrate produced from the milling or concentrating stage of mineral processing to the metal content in the ore feed, usually expressed as a percentage. For example, a mill recovery factor of 92 percent may be achieved in upgrading a 5-percent zinc ore to a 50-percent zinc concentrate. The remaining 8 percent of the zinc content in the mill feed is lost in the waste or tailings reject from the concentrating process.

- Mine Capacity:** scale of a mining operation expressed in terms of the amount of ore and waste rock which it is possible to extract per unit time. Mine capacity may be specified by such measures as tonnes per shift, tonnes per day, or tonnes per year.
- Mineral Deposit:** a particular concentration of minerals in the earth which would justify production for specified economic conditions and currently feasible or near-feasible technology of production.
- Mineral Exploration:** sequential process of integrating geoscience concepts with various geological, geophysical, geochemical, and drilling technologies, to generate and interpret information for the purpose of discovering and delineating economic mineral deposits.
- Mineral Resources:** total concentration of minerals in all mineral deposits which would justify production for specified economic and technological conditions. Mineral resources are usually classified for assessment purposes into known, unknown, economic, and subeconomic categories.
- Open Pit:** common method of mining mineral deposits which occur at or near the surface. To apply this method, surficial soil and waste rock is removed during the preproduction period, exposing the deposit for mining. Ore reserves are then systematically extracted from the top of the deposit down, recovering ore and removing the associated waste until the ultimate horizontal limits and depth of the open pit are reached.
- Operating Cost:** expense required to keep a mine running and producing. Operating costs fall into three major classifications: direct, indirect, and general (overhead). Direct costs, including operating labour and supplies, tend to be proportional to the rate of production and, therefore, are also termed "variable costs". Indirect costs, such as administrative and technical services, property taxes, and insurance, tend to be independent of throughput and, thus, may be referred to as "fixed costs". General or overhead expenses usually represent off-site

corporate-level costs which are allocated to the operating units.

- Ore Grade:** average quantity of valuable mineral or metal contained in ore reserves expressed per unit weight such as "grams per tonne", or as a percentage.
- Ore Reserves:** the known-economic subset of mineral resources for a particular deposit or aggregated for all deposits. Ore reserves are usually classified into categories such as proven, probable, and possible, based on the amount of sampling information available and the perceived reliability of estimates.
- Polymetallic Deposit:** deposit which contains several recoverable and saleable metals; for example, a copper-zinc-silver, copper-molybdenum, zinc-lead-silver, or copper-gold deposit.
- Porphyry Deposit:** type of disseminated base metal deposit characterized by very large size, relatively uniform distribution of economic minerals, and low grade. Porphyry deposits may contain copper only, copper-gold, copper-molybdenum, or molybdenum with or without tungsten.
- Preproduction Development Period:** number of years required to bring a mine into commercial production, measured from the point in time when a development decision is taken. The required mine capacity is developed and equipped, and related mineral processing and infrastructure facilities are constructed, during this period.
- Productivity:** the efficiency of production or, in other words, the rate at which output flows from the use of given amounts of the factors of production (inputs).
- Quality of Mineral Resources:** the geological character of mineral deposits reflected by such facets as deposit size, geological grade, geographical location, ore width, depth below surface, mineralogical complexity, and geotechnical properties.

Recoverable Ore Reserves: estimate of the tonnage and grade which will actually be mined and fed into the mineral processing facility. Ore reserves are initially estimated as in-ground geological values. Mine recovery and dilution factors are subsequently applied to these geological estimates to predict the tonnage and grade recoverable.

Refining: process for purifying the metal product from a smelter to industrial end-use specifications, and recovering associated precious metals. For example, a 99-percent blister copper smelter product may be electrolytically refined to yield 99.9%-percent copper anodes. The anodes may then be melted down and cast into various commercial shapes such as wirebars. Precious metals are recovered and refined from the electrolytic tank residue in a separate process.

Sedimentary-Hosted Deposit: type of massive sulphide base metal deposit associated with shale or carbonate sediments. Sedimentary-hosted deposits, containing zinc and lead with possible copper and silver byproducts, tend to be of medium size and grade.

Smelter Payment Terms: conditions for the sale of a base metal concentrate from a mine to a smelter. These terms include price payment specifications for the primary metal, unit deductions for metallurgical losses, treatment charges, and credit and penalty provisions for other contained metals. The combined effect of any set of smelter payment terms may be shown by expressing the market value of metal contained in a concentrate as a percentage of the refined metal price. For example, the revenue received by a mine for copper in concentrate form might represent 70 percent of the refined copper price, while 50 percent of the refined zinc price might be paid for zinc contained in a zinc concentrate.

- Smelting:** reduction process which converts metallic minerals contained in a base metal concentrate to an impure metal product. For example, a concentrate containing 25-percent copper in the form of chalcopyrite (a copper sulphide) may be roasted to produce a 30-percent copper calcine, then melted in a reverberatory furnace to form a matte. The molten matte, which may grade 45-percent copper, is then transferred to a converter furnace where the copper is reduced to its elemental state. The molten "blister" copper, now about 99 percent pure, is cast into shapes known as "anodes" for electrolytic refining.
- Stope:** basic unit of production for an underground mine. Each block of ore is initially developed, and then systematically drilled and blasted. Broken ore is conveyed to the central mine workings en route to the processing plant. Various stoping procedures may be employed including shrinkage, cut-and-fill, blasthole, and caving methods.
- Stripping Ratio:** ratio of the amount of waste to the amount of ore extracted from an open pit mining operation.
- Structural Market Trend:** change in market conditions which is of a permanent nature arising, for example, from technological change in existing end uses, the creation of new product markets, or the development of substitute materials.
- Tailings:** final low-grade waste reject from a mineral processing plant, disposed of in slurry form into a tailings pond containment.
- Total Factor Productivity:** measures the efficiency with which all of the factors of production combined are employed in production.

Underground Mine: method of mining employed when it is not feasible to develop an open pit. A deposit is accessed for underground mining by means of vertical shafts, spiral declines, and horizontal haulage ways. Individual blocks of ore are developed and prepared for mining using smaller-scale cross-cuts, drifts, and raises. Various stoping methods are then employed to extract the ore blocks.

Volcanic-Associated Deposit: type of massive sulphide base metal deposit formed in active tectonic zones and occurring through the entire geological time frame. Volcanic-associated deposits are typically small and high grade.

Waste: barren or low-grade rock adjacent to or included in a mineral deposit which must be extracted in the mining process either separately or together with the geological reserves recovered.

Working Capital: part of the capital cost of a project required to finance the time lag between payment of operating costs and receipt of sales revenues. The working capital requirement may vary from the equivalent of 2-3 months operating costs for well-situated projects to 15 months operating costs at remote locations.

APPENDIX

CLASSIFICATION OF CANADIAN BASE METAL DEPOSITS

BY DEPOSIT TYPE AND DISCOVERY DATE

Volcanic-Associated Massive Sphide Deposits

Pre-1946 Discoveries

ALDERMAC
AMOS
AMULET A
AMULET C
AMULET F
BIG BULL & TULSEQUAH
CHIEF
BOB
RONANZA
BRITANNIA
BRUCE
BUCHANS
CAPELTON
COPPER-MAN
CUPRUS
DICKSTONE
EAST SULLIVAN
EUSTIS
FLIN FLON
GOLDEN MANITOU

GULLBRIDGE
HIDDEN CREEK
HORNE
JOLIET
KAM KOTIA
LITTLE BAY
NORMETAL
OLD WAITE
QUEMONT
RAMBLER MAIN
SHERRIDON
SUFFIELD
TILT COVE
TURNBACK
VAMP LAKE
WAITE DFAULT
WEEDON
WEST MACDONALD

1946-53 Discoveries

BARVUE
BELFORT
BIRCH LAKE
BRUNSWICK 6
BRUNSWICK 12
CONIAGAS
COPPERCORP
CORONATION
EAST WAITE
FLEXAR
GECO
GRANDUC
HUNTINGTON

INDIAN MOUNTAIN
KEY ANACON
MCLEAN
MUNRO COPPER
NORTH STAR
OSBORNE LAKE
ROTHERMERE
SCHIST LAKE
TEMAGAMI
VENDOME
WILLECHO
WILLROY

1954-1961 Discoveries

BARVALLEE
BELL ALLARD
BIG NAMA CREEK
CARIBOU
CHISEL LAKE
CLEARWATER
CORBET
CUPRA
FOX
GARON LAKE
GHOST LAKE
HALFMILE LAKE
HIGH LAKE
JOUTEL
JUNGLE
LITTLE RIVER
LYNX

MATTAGAMI
MURRAY BROOK
NEW HOSCO
NORBEC
ORCHAN
ORIENTAL NO. 2
PATER
PINEBAY
POIRIER
SOLBEC
STALL
THIRD PORTAGE LAKE
WEDGE
WHALESBACK
VAUZE

1962-69 Discoveries

ANDERSON LAKE
CENTENNIAL
COPPER-LODE A
COPPER-LODE E
DELBRIDGE
DIXIE
EAST
EMBURY LAKE
GREAT BURNET LAKE
JAMELAND
JAMIESON
KIDD CREEK

LOUVEM
MATTABI
MILLENBACH
NORITA
RAIL LAKE
REED LAKE
ROD
RUTTAN
SOUTH BAY
STRATMAT
WHITE LAKE
WIM

1970-77 Discoveries

AGRICOLA LAKE
CAPE RAY
CHUCHUA CREEK
DETOUR A1
DETOUR A2
DETOUR B
F GROUP
GOLDSTREAM
GRASSET LAKE
HACKETT
HOOD RIVER
IZOK LAKE
KUTCHO CREEK
LEMOINE

LESSARD
LOST LAKE
LOUVEM ZINC
LYON LAKE
MAGUSI
MING
MYRA FALLS
NEW INSCO
SCOTT
SPRUCE POINT
STURGEON
SYLVIA
WESTARM

Sedimentary-Hosted Massive Sulphide Deposits

Pre-1946 Discoveries

ERRINGTON
LUCKY JIM
NEW CALUMET
REEVES

SILVER GIANT
SULLIVAN
VERMILLION

1946-53 Discoveries

BLUEBELL
HR
JERSEY
MINERAL KING

PINE POINT 1
TOM
VANGORDA

1954-61 Discoveries

NANISIVIK
WALTON

1962-69 Discoveries

ANNEX
CORONET
DANIEL'S HARBOUR
ECLIPSE
FARO

PINE POINT 2
PYRAMID
SALMON RIVER
SWIM LAKE

1970-77 Discoveries

ANNIV
BEAR TWIT
CIRQUE
DY
GAY'S RIVER
GAYNA RIVERGREAT SLAVE
REEF
GRUM

HOWARD'S PASS
JASON
MEL
NADALEEN RIVER
PINE POINT 3
PINE POINT 4
POLARIS
ROBB LAKE

Porphyry Deposits

Pre-1946 Discoveries

COPPER MOUNTAIN

1946-53 Discoveries

-

1954-61 Discoveries

BETHLEHEM
GLACIER GULCH
KITSALT

1962-69 Discoveries

ADANAC
BELL
BERG
BOSS MOUNTAIN
BRENDA
CATFACE
CASINO
CARIBOO BELL
ENDAKO
GALORE CREEK
GIBRALTAR

GRANISLE
HIGHMONT
HUCKLEBERRY
INGERBELLE
ISLAND COPPER
LORNEX
MORRISON
SAM GOOSLY
SCHAFT CREEK
VALLEY COPPER

1970-77 Discoveries

AFTON
JA
MAGGIE
RED

Other Base Metal Deposits

Pre-1946 Discoveries

BEST CHANCE
CAMPBELL MAIN
CEDAR BAY
DUNRAINE
GASPE COPPER MOUNTAIN
HYERS ISLAND
INDIAN CHIEF
KEEWENAW
LACORNE
MERRILL ISLAND

MOTHER LODE & SUNSET
NEEDLE MOUNTAIN
ORO DENORO
PHOENIX
PREISSAC
SNOWSHOE
SPRINGER
STIRLING
TROJAN
WAR EAGLE

1946-53 Discoveries

BLUE GROUSE
CHIBOUGAMAU EXPLORERS
COPPER RAND
COWLEY PARK

GRANDROY
JACULET
KOKKO CREEK
WADEN BAY

1954-61 Discoveries

ANGLO AMERICAN
BOUZAN
COPPER CLIFF
CRAIGMONT
HENDERSON
LITTLE CHIEF

MAGNUM
PERRY
PORTAGE
QUEBEC CHIBOUGAMAU
SCHUMACHER COPPER
SUNRO

1962-69 Discoveries

BENSON
COOKE
DAVIS KEAYS
GEM
HARPER CREEK
HOPE LAKE
ICON

JUNE
MADELEINE
OK
RED MOUNTAIN
REDSTONE COPPER
ROBATAILLE
TRIBAG

1970-77 Discoveries

GWILLIAM
MINTO
RIOCANEX OBALSKI

SUSTUT
TROUT LAKE

THE AUTHOR

Brian W. Mackenzie, a native of Winnipeg, was born in 1939. He holds a B.Eng. (honours) in mining from McGill University, an M.Sc. in mineral economics from the University of the Witwatersrand, and a doctorate in engineering science (mineral economics) from Columbia University. After working as an engineer in mines in Canada and South Africa, he became an assistant inspector of mining leases for the South African government, and later worked as a mineral economist with Energy, Mines and Resources Canada. Dr. Mackenzie joined McGill University in 1968 where he was responsible for teaching and research in mineral economics, and was director of the mining program until 1977. In January 1978 he became a research associate of the Centre for Resource Studies and a professor in the Department of Geological Sciences at Queen's University. In 1979 Dr. Mackenzie was named distinguished lecturer in mineral economics by the Canadian Institute of Mining and Metallurgy, and in 1983 he received their "Robert Elver Mineral Economics Award". He has presented mineral economics seminars in Canada, Australia, Brazil, Chile, China, Indonesia, South Africa, Sweden, Tanzania, and the United States.

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